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3D ENGINEERING WORKSTATION AND CONNECTED ENGINEERING

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The purpose of this Phase I research project was to determine the feasibility for developing a 3D Engineering Workstation for designing custom precision forgings. An industrial advisory board was formed to guide the research, and it consisted of members from USCAR corporations, national laboratories and the parts supplier industry. Rules were developed for designing a graphical user interface (GUI) for non analyst designers, and emphasis was placed on linking discreet simulations of different processes, e.g., forging, quenching and heat treatments, which are needed for producing a finished part. Gleeble testing was done, and the results show that thermal gradients can have a significant effect on the mechanical properties of aluminum alloy 7050. The inverse FEM was evaluated for determining surface heat transfer coefficients, and the feasibility for using thermal probes with important geometrical features of the part was shown to be a viable way for handling complex 3D geometries. The results of this work can be used to develop a design system for making custom netshape forgings more affordable for the DOD. The precision forging of netshape aerospace and automotive parts is of prime interest, because netshape forgings save energy, materials and reduce overall part cost.

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EXECUTIVE SUMMARY

The major thrust of the Department of Defense (DoD) is processing technology to manufacture and sustain defense products affordably and with world class quality. Most manufacturing technology efforts are focused on three core competencies:

• Manufacturing Process Maturity	• *Process understanding to reduce production risk*
• Manufacturing Process Control & Improvement	• *Affordable critical components, remanufacture support and design feedback*
• Industrial Base (IB) Risk Reduction	• *Affordable access to defense critical IB capability*

Major cost reductions are being sought in turbine engine and airframe products. Research under this Phase I SBIR was directed to understanding the issues related to doing connected simulations of discrete processes needed for producing a finished part. The initial objective was to properly address process design and material behavior at two possible levels of simulation: (1) isolated simulation and (2) connected simulations. The detailed simulation considers the isolated processes of forging, quenching and machining.

Most custom part manufacturing operations uses a mix of software applications to understand isolated processes for the purpose of reducing production risk, and, in addition, most of these analysis applications are not designed to consider a sequence of processes. The controlling driver in this research was cost reduction for forged components, because cost reduction is expected to contribute significantly to reduction of acquisition costs for new military and commercial airframes. This Phase I SBIR effort was concerned primarily with three-dimensional structural airframe components, because the Air Force had a companion program dealing with the cost reduction of manufacturing axisymmetric gas turbine engine disks. This SBIR project makes use of the finite element method of analysis for handling the complex geometries and process details, whereas the companion SBIR project is making use of simplified analysis models such as the slab method of analysis for optimizing the forging process for engine disks.

Some OEM, i.e., original equipment manufacturers, have set an objective of lowering airframe acquisition costs by 25 percent. This very aggressive goal for airframe component cost reduction brings the relative processing requirements and cost performance of different product forms used by the airframe OEM into focus. Custom precision aluminum forgings have been a preferred product form for airframe structures, because forged components historically have superior mechanical properties and life cycle performance attributes. These components are typically used in critical structures.

However, custom precision forgings are being replaced for some applications by thick plate hogouts, because precision forged parts can be scrapped frequently when machining distortions are encountered. Therefore, it is necessary to design a *quench path* that minimizes residual stresses and subsequently machining distortions. The performance cost of precision forged parts can be reduced by realizing enhanced machining performance and lower customer fabrication costs for components machined from forged aluminum parts.

The importance of designing for enhanced machining performance and lower fabrication cost for components produced by netshape processing is not unique for forged aluminum products. All netshape or near netshape products have this as a common problem. Because of the importance of minimizing residual stresses in all netshape products, one of the major tasks for this Phase I effort focused on software for determining the thermal physical properties and boundary conditions, which are needed for simulating thermal processes such as quenching and solidification.

The inverse finite element method (FEM) was investigated, because one of the all-important difficulties associated with numerical simulation of thermal processes is solved by being able to determine the surface heat transfer coefficients, thermal conductivity and heat capacity from careful experimental measurements of temperature as a function of position and time. Because residual stresses are a result of thermal gradients associated with quenching processes and component geometry, the effect of thermal gradients on the mechanical behavior during cooling was explored. These efforts address essential processing steps that connect deformation process

analysis with quenching path and distortion analysis, which are associated with the discrete processes of heat treatment and machining.

The aerospace and automotive enterprises have many design challenges to overcome. Today's market environment is dynamic, and these enterprises face the challenge of timely product development. Simulations that take advantage of increasingly faster and cheaper computers must be used routinely to speed product design. Both product and process design engineers still do manual iteration to optimize a product or process design, and difficulties still arise from the challenge of bringing multidisciplinary design knowledge to bear on an integrated product design process. Design is a three-core problem:

- Coupling — *designers think locally, but they are tightly coupled to other designers.*
- Prioritizing — *designers do not have a common language for comparing the importance of issues.*
- Planning — *design tasks cannot be sequenced in detail. It is possible to plan at a high level, but it is impossible to do details.*

Overcoming these obstacles is a priority for industries, which need to reduce cycle time, reduce cost and produce superior products. In today's environment, product and process designers must become proficient with a number of different software applications, and they must understand each application's idiosyncrasies. During this Phase I research, the type of framework that is required for doing connected and multidisciplinary process design was investigated. The design of a graphical user interface was considered from the perspective of applying user-defined design knowledge with state of the art optimization techniques to free time for doing other tasks that require more skilled designer tasks.

The major anticipated benefits of this project will be to dramatically cut the time that elapses between part order and delivery. The OEM's will have lower carrying costs, and shorter lead

times will benefit the DoD and U.S. Manufacturers by letting them specify orders for parts closer to the time they need a component. Shorter lead times also address the Air Force's and DoD affordability and sustainment thrusts, which is a big plus for a fast-changing defense business. It will solve a major part shortage problem, including dies, jigs and fixtures, which all original equipment manufacturers face to meet ambitious delivery schedules. If this program were to become a Phase II SBIR or ManTech program, it potentially could have a major impact on cost reductions in turbine engine and airframe products, and reduce the cost of ownership. The design and optimization system will significantly improve the following: (1) Process understanding that reduces production risk; (2) Remanufacturing support, design feedback and affordable critical components; (3) affordable access to defense critical industrial base capability.

PURPOSE OF THE WORK

The purpose of this Phase I SBIR work is to determine the feasibility for developing a 3D Engineering Workstation for doing connected simulations and competing in today's dynamic market. Today's dynamic market environment creates many design challenges for the aerospace and automotive enterprises to overcome. These enterprises face the challenge of timely product development, and simulations that take advantage of increasingly faster and cheaper computers must be used to speed product design. Both product and process design engineers still do manual iteration to optimize a product or process, and major difficulties arise from the challenge of distilling multidisciplinary design knowledge into an integrated design process. In doing connected simulations, process designers must become proficient with a number of different simulation software applications, and they must understand each application's unique idiosyncrasies.

One of the goals of this Phase I research was to investigate the technical requirements of doing connected simulations of discrete processes and more fully understand the user interface requirements that designers, who are not trained in numerical analysis, may have. This interface should be a framework for overcoming the design challenges that face process designers. A

second goal of the Phase I research was to find or develop a robust method for determining the surface heat transfer coefficients, thermal conductivities, and heat capacities from careful experimental measurements of temperature as a function of time and position. This software application is needed to overcome one of the all-important difficulties associated with numerical simulation of thermal processes, which is to determine the surface heat transfer coefficients, thermal conductivity and heat capacity using a thermal probe and using careful measurements of temperature as a function of time and position within the probe. A third goal was to determine whether the mechanical properties of an important aluminum alloy forging material are sensitive to thermal gradients, which are typical of those found in forgings during quenching from a forging temperature.

Organizing an Industrial Advisory Board to provide technical guidance and help define the scope and statement of work for Phase 11 research was another important purpose of this Phase I research. The members of the advisory board were chosen because of their knowledge and experience in product and process design. Members of this board also had a need for an advanced engineering workstation that makes it easy to do connected simulations of discrete processes, and they also expressed a willingness to evaluate the design and analysis technologies in their corporations. The advisory board members had an additional responsibility of providing technical data that was too costly to develop with the resources available for Phase I research.

Statement of Work

Task I **Form an Industrial Advisory Committee:** The objective of this task is to form an advisory team that will provide guidance and insight into the sequence of forging design and manufacturing sequence and get their commitment to participate in validating the new capability for designing machining-friendly forgings.

Task II **Design and Show a Prototype Interface for Doinm Connected Simulations:** The objective of this task is to design a graphical user interface to make it easy to use by product

and process design engineers who are not specifically trained as analysts to do connected or linked simulations.

Task III **Develop Constitutive Relations for Predicting Residual Stress Patterns that Develop During Quenching:** The objective of this task is to develop constitutive relationships that describe the mechanical properties of the workpiece material as a function of cooling rate and temperature.

Task IV **Develop a Practical Methodology for Generating the Surface Heat Transfer Coefficients, Thermal Conduct , Heat Capaciiy Database for Quench Path Conceptual Design and Accurate Residual Stress Predictions**: The objective of this task is to develop a database and a method for rapidly determining the effective surface heat transfer coefficient h that is determined by geometrical shape complexity, type of quenchants and the different possible quench phases, which include film boiling, where heat transfer is low; nucleate boiling, where heat transfer rates become high, and convection, where the surface temperature decreases below the liquid's boiling point.

Findings or Results

Task I **Form and Industrial Advisory Committee**: An Industrial Advisory Committee was formed that provided guidance and specifications for developing a family of probes and an inverse finite element methodology for determining the surface heat transfer coefficients. These coefficients drive the local rate of heat extraction from the component. In general, this coefficient is found to be a function of the quenchant temperature, the local surface temperature of the component, part geometry and the location on the component, and surface condition.

UES, Inc. is a full member in the National Center for Manufacturing Science (NCMS), which has a collaborative Predictive Heat Treatment Project. The consortium is comprised of the

following team members:

Ford Motor Company

General Motors Corporation

The Torrington Company

Deformation Control Technology, Inc.

The MacNeal-Schwendler Corporation

IITRI Instrumented Factory

Sandia National Laboratories

Oak Ridge National Laboratory

Los Alamos National Laboratory

Lawrence Livermore National Laboratory

Colorado School of Mines

J. P. Industries, Inc.

The objective of this NCMS project team is to develop a methodology and the computer simulation capability to predict component response, i.e., distortion, residual stress, microstructure, etc., to carburizing and quenching. The simulation capability was to be available as a user-friendly tool functioning on a workstation. Such a tool would enable *virtual process development and virtual process optimization* by predicting process limitations, microstructures, material properties, and residual stresses.

The successful prediction of component response to quenching and other heat treatment processes such as carburizing requires many elements, including the following:

1. A detailed knowledge of the component boundary conditions from both the furnace (forging dies) and the quench

2. The ability to accurately model the mechanical, thermal, and metallurgical response of the material during processing

3. A numerically efficient methodology (an efficient inverse method) to perform calculations on complex geometries.

Three technical areas of collaboration for this Phase I research were defined as a result of meetings with the committee members, and these areas are as follows:

1. Data Analysis: the NCMS Team shared cooling curve data from a recent experiment with UES so that UES could apply the latest release of ProCAST's inverse code.

2. Quench Probe Design Rules: UES shared the development that it is doing with Ohio University to design a series of quench probes that will be sufficiently large to represent typical components being heat treated. UES and Ohio University shared its progress and accomplishments with the NCMS Team in exchange for the opportunity to discuss their developments with the NCMS Team and utilize any advice given by the team. One of the mechanisms for exchange included the exchange of input decks between the two teams to try various calculations and compare results.

3. Inverse Code Development: In exchange for the above collaboration, UES and Ohio University provided inverse code solutions to the NCMS Team. Lawrence Livermore worked with the same data that was given to UES and Ohio University to compare results for calculations of h values. The new ProCAST inverse method produced results that were in excellent agreement with those obtained by the Lawrence Livermore National Laboratory. The SBIR team will continue to collaborate with the NCMS Heat Treatment project team beyond the Phase I research. The end product of this collaboration is expected to be improved algorithms for robust 3D analysis.

Initial guidance was provided by the Industrial Advisory Committee prior to starting any

research on the project, and these recommendations include the following advice:

1. To have a method that will be used by industry, the SBIR Team should develop an algorithm that is robust with respect to the analysis of 3D components, which have different surface features and shape complexities. The SBIR Team should think of a family of geometrical probes rather than a singular probe, and accuracy of surface heat transfer coefficient analyses are less important to industry than the ability to robustly treat different geometries and surface finishes.

2. The tool has to be usable by process engineers and designers, making the interface development an essential part of the development.

3. The tool had to be based on commercially available and supported software. The user interface must provide access to geometric modelers, a meshing tool, a finite element solver and a graphical post-processor. An important capability of the finite element solver is that it should allow the possibility for user-defined microstructure, mechanical and thermal subroutines. A database should be provided for microstructure, mechanical and thermal behavior. A necessary function of the interface is that the user must be able to assign material properties, process parameters, and a process schedule. These data are contained in databases that are accessed during model building. This advice was deemed to be very important for Phase III software commercialization, and the SBIR Phase I research followed these guidelines.

The Industrial Advisory Committee provided the SBIR Team experimental data from a gear blank geometry for evaluating the inverse FEM, which is part of the UES developed ProCAST™ software application for simulating industrial thermal and solidification processes. The research done to evaluate surface heat transfer coefficients will be discussed as part of the Task IV findings.

Task II **Design and Show a Prototype Graphical User Interface**: Research was done to define the requirements of a graphical user interface (GUI) that would make is easier to do connected simulations. Connected simulations involves linking all of the unit or discrete processes that are required for manufacturing a custom netshape part such as a precision forging or casting. The rules, which were provided by the provided by the NCMS Consortium, were factored into this study. The general rules that guided our initial study are given as follows:

- The GUI will enable the *tool* to be used by process engineers and designers who are not specifically trained as analysts.

- The tool will operate on either a PC Workstation or UNIX Engineering workstation. The Tool will be based on commercially available and supported software.
- The GUI will provide access to geometric modelers such as ACIS and Parasolids, a meshing tool such as MeshCAST™, a finite element solver such as ANTARES™ and ProCAST™, which have a capability for *user-definable* subroutines for mechanical, thermal and microstructural behavior. A necessary function of the GUI is to facilitate the non-analyst user in assigning material properties, process properties, process parameters, and even a process schedule. These data will be contained in a databases, which can be accessed during model building.

A set-based knowledge system for doing die sequencing, preform design, die design, die life prediction, and establishing the conditions for satisfying admissibility requirements for the preform shape will need to be created by considering case histories developed by experienced die design practitioners.

A flow chart showing information flow for a finite element-based process model is shown in Figure (1)

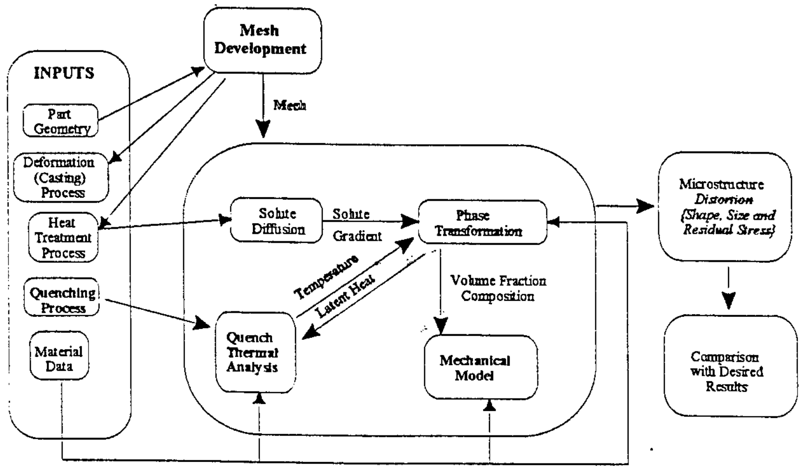

Figure 1 Finite Element Based Process Model

The boxes in Figure (1) show the major pieces of the process model. The user first builds the component geometry by entering a part definition file. The geometry is subsequently meshed automatically, with the user having control over mesh density and grading. Simultaneously, surfaces are automatically identified for later application of boundary conditions. The GUI provides choices for the user to select a material, the material property data set, and the definition of the process to be simulated. Assuming that ANTARES is the solver, the GUI assembles ANTARES input data from this information — ,i.e., the mesh, material properties and boundary conditions for the heat treatment, thermal and mechanical models to be executed.

A prototype graphical user interface (GUI) has been built and demonstrated on a Windows NT PC Workstation. This GUI leverages the familiar and user-friendly Windows 95 look-and-feel. By enabling only the relevant menu options at a particular stage, the interface guides the user through a required sequence of steps for setting up a simulation problem. The interface features

customizable tool bars for quick access to various functions. It also makes extensive use of *property sheets* for easy input information such as material data.

An all-important goal in the design of the graphical user interface is to enable the tool to be integrated seamlessly and deployed effectively in the industrial environment. One of the main criteria is therefore the tool's ability to import as well as manipulate geometric models from industry standard sources such as ACIS and Parasolids. The use of SolidWorks™ to provide such facility has been investigated. SolidWorks is a very powerful PC-BASED 3D geometric modeler. More important, it also provides a set of open API's (Application Programming Interface). By exploiting the open API feature, the capability of SolidWorks can be embedded into the graphical user interface. This would, for example, allow the user to directly manipulate the geometric model from within the user interface, based on information provided by a previous simulation. In addition, utilizing Windows' OLE (Object Linking and Embedding) technology, design data as well as simulation results can be easily incorporated into other applications such as spreadsheet and word processor applications. In conjunction with this, industry standards, such as STEP, must be incorporated in the interface to ensure that the tool interoperates with a whole range of standard-based products.

Wind/U is a PC-to-UNIX porting tool, and it was evaluated to determine its effectiveness in porting a PC developed software application to the UNIX platform. By effectively providing a complete Windows development and runtime environment under UNIX, the product enables us to port the PC prototype to run on a DEC/ALPHA workstation in a very short time - about three hours. The result faithfully reproduced the familiar Windows look-and-feel without compromising the performance.

This research has proven feasibility for developing a simulation environment that can operate either on a Windows NT PC Workstation or a UNIX Engineering Workstation. This development satisfies the requirement that the "design tool" be based on commercially available and supported software.

Industries that would use this new Product/Process design environment face the challenge of timely product and process development, as today's market environment is dynamic. Even with the improved GUI described previously, engineers will still confront the tedious task of manual iteration and the challenge of transforming a design team's multidisciplinary knowledge into an integrated design process. Process designers still have to become proficient in using a mix of simulation software and fully understand each application's idiosyncrasies. Overcoming these obstacles is a priority for all industries that need to reduce cycle time, reduce cost, and produce superior products to be competitive in a dynamic, world marketplace.

A Knowledge Integrated Design System (KIDS) was developed by the Air Force (Contract No. F33615-89-C-5659) for overcoming these design challenges. Workflow management, process modeling and information technologies were integrated using a Knowledge Integration Shell (KI Shell™) to make the part supplier industries more competitive. More than five engineering disciplines were integrated by this tool, and these disciplines included mechanical design, process simulation, stress engineering, thermodynamics, and materials science. Some of the benefits of the design system were as follows:

- Improved Design Laps Time from 5 to 1
- Improved Design Time from 13 to I
- Captured the Ability of Experienced Engineers
- Dramatically Reduced Training for New Users
- Remembered and Interpreted Design Rules in a Consistent Way Each Time
- End User Developed Flowcharts Converted Into Process Management Software
- Standardized the Design Process and Reduced Mistakes

This KIDS approach satisfies some of today's design challenges, but it fails to deal with the tedium of manual iteration. To rapidly do connected simulations, a framework is needed that automates the use of simulation and analysis software and combines optimization techniques with human knowledge. This approach combines the advantages knowledge integration, as

demonstrated by the KIDS program, with state of the art optimization. This combination will lead to improved product designs in less time.

A computer-aided optimization (CAO) environment tool for doing multidisciplinary design processes was found to be commercially available, and it satisfies the requirement of being a commercially supported product. A software shell known as iSIGHT™ automates the repetitious job of running programs. It applies user-defined knowledge with state of the art optimization techniques as it executes simulation and analysis programs. iSIGHT combines the power of optimization, automation, and integration technologies into a single application shell, and it can easily be customized to suit the needs of any company.

Software applications such as ANTARES, ProCAST, SolidWorks, which are needed for doing connected simulations, can be integrated using library procedures that allow programmers to mix and match customer specific third party interfaces, analysis tools, and optimization techniques. iSIGHT runs on popular UNIX and Windows NT workstations.

Therefore, it is feasible to satisfy the industrial requirements defined by the Industrial Advisory Team and users of process analysis tools by using a CA0 environment such as iSIGHT to create an advanced Knowledge Integrated Design System that can reduce cycle time, reduce cost and produce superior products.

Software Speedup

The feasibility of using the three dimensional tetrahedral element for finite element analysis with elastoplastic material has been investigated. The rationale for why 3D tetrahedral elements are required for process modeling using the Rigid-Viscoplastic, Rigid-P/M Viscoplastic and Elastoplastic (EP) finite element method (FEM.) is provided..

In the FE forming simulation, the finite element mesh distorts as the simulation proceeds. At some point of time elements are so distorted that the analysis can not continue. In order to simulate the whole forming process, the finite element mesh has to be regenerated. This is called *rezoning or remeshing.* In the past, this was done manually or interactively between the finite element solver and the mesh generator. Because most forming simulations require remeshing, some of them need remeshing almost every step of the analysis, it is important that we select an element type that is easy for the automatic remeshing. In three dimensions (3D), at the moment, the tetrahedral element mesh is the only mesh that can be automatically regenerated according to the given mesh density and the geometry.

Most of the finite element software for bulk forming simulation use the rigid-viscoplastic material, because the elastic deformation is very small compared to the plastic deformation. However when residual stress is the main concern in the analysis, the analysis requires the elastoplastic (EP) model.

Tetrahedral elements with 4 nodes and using the standard finite element formulation can not correctly analyze the forming process, because the material incompressibility constraint causes *locking* in the analysis, i.e., the element is too stiff for deformation. A mixed form formulation was proposed (see Zienkiewicz) to solve the stiffness problem. The *v*-p mixed form formulation (see Hughes), which solves nodal pressure and velocity field, can be used to remove this element locking problem.

The theory for the *v*-p tetrahedral form is briefly outlined.. The mixed form formulation splits the formulation into two parts, one related to contribution of the deviatoric part of the stress tensor and one related to the volumetric part. This can be summarized in the following FE equation:

$$\begin{bmatrix} K & Q \\ Q^T & C \end{bmatrix} \begin{Bmatrix} v \\ p \end{Bmatrix} = \begin{Bmatrix} F \\ o \end{Bmatrix}$$

where v is nodal velocity vector and p is pressure vector. K is the stiffness matrix comparable to the standard FE formulation. F is the external force vector. Q and C are matrices contributed by the volumetric separation. The Crank Shaft figure (2) shows the state of the art of simulation capability using the v-p tetrahedral formulation. Over 300% plastic strain is reached during this simulation.

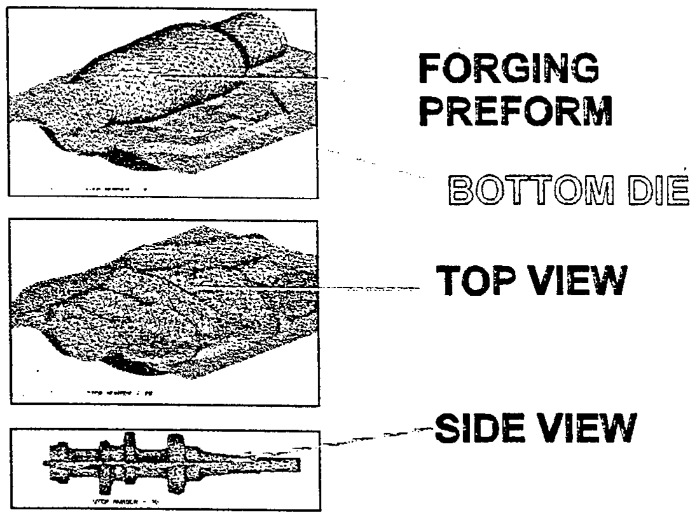

Figure 2 Crank Shaft Forging with Large Finite Deformations

This mixed form of the tetrahedral element was shown to work well for powdered materials during the course of this research. To make FEA more efficient, a new approach is being investigated for speeding-up computation. Feasibility is being studied for condensing the pressure term from the tetrahedral v-p approach to further reduce the computation time. The ANTARES application can now do calculations with tetrahedral elements that were once done using hexahedral elements.

The requirements, which were defined by the Industrial Advisory Committee and users of process analysis tools, can be achieved by using a commercially available CAO environment such as iSIGHT and by implementing new formulations of the mixed v-p tetrahedral element, which speed up the simulation process and enable all of the process physics to be modeled.

Task III **Develop Constitutive Relations for Predicting Residual Stress Patterns**:
Many metallurgical and external process factors influence the final microstructure, residual stress, and distortion that occur after quenching and subsequent thermomechanical treatments. Calculating small dimensional changes associated with quenching requires a high level of detail in terms of material data and process data. The scale of these calculations must be sufficiently small to capture the local metallurgical changes from the surface of the component to the core. This Phase I research focused only on major first-order effects to generate a base working model for residual stress and distortion analysis. Thermal gradients created during quenching cause the first-order effects. The gradients result in thermal and transformation-induced strains that cause local plasticity.

Predicting residual stress patterns during quenching depends on knowing how the yield strength of the workpiece material varies with the cooling rate $\dot{T}$, the temperature T, and the thermal gradient . The accuracy of residual stress and displacement predictions depends strongly on using the right database for EP modeling. This exploratory research investigated the sensitivity of 7050 aluminum alloy to temperature and thermal gradient. The effect of thermal gradient on the mechanical properties of 7050 aluminum alloy was evaluated using the Gleeble Testing machine.

Test Conditions

A Gleeble 3500 Model testing machine was used for the tests. This system has a maximum speed of 1000 mm/s and a static force of 10 metric tons. The maximum heating rate achievable is 10,000°C/s. The test specimens were heated to a peak temperature of 400°C at a given heating rate of 10°C/s, held for 30 seconds, and cooled at a given cooling rate (0.5°C/s, 5°C/s, 50°C/s, 100°C/s, and 200°C/s) to the test temperature of 150°C. The specimen was tensile tested immediately when the test temperature was reached, and it continued until failure occurred. The strain-rate was 1/s, and all tests were run in air.

Test Results

The test results show that cooling rates from 50°C/s to 200°C/s did not have a significant effect on the mechanical properties. However, the cooling rate from 0.5 C/s to 50°C/s significantly affected the mechanical properties. The change of the mechanical properties could be affected (more or less) by the change of the axial thermal gradients at the test temperature. At the fastest cooling rate of 200°C/s, the specimen had a mean axial thermal gradient of about 35 C/mm at 150°C, and, at the slowest cooling rate, it had a mean axial thermal gradient of 26 C/mm. The mechanical properties for aluminum alloy 7050 are shown in Figure (3). Figure (4) shows a typical heating and cooling cycle to the tensile test temperature, and Figure (5) is a Gleeble Stress Strain curve for this material subjected to the conditions shown in the figure. The engineering strain is shown in Figure (6) as a function of time, and the slope of the curve is the strain-rate.

The critical temperature range for aluminum alloy 7050 is 400 - 200°C (725 - 400F),[1] and, within this temperature range it is desirable to have as slow cooling rate of the order of 10°C/sec. This relatively slow cooling rate is needed to allow the thickest region of the forging to approximately the same temperature as the surface region of the forged part. It was postulated in the early 1980's that this cooling rate was needed to achieve satisfactory mechanical properties in quench sensitive Al-Zn-Mg-Cu 7XXX alloys such as 7050 . Below 200°C (~400 F), these alloys can be quenched at much more convenient rates. These results appear to show that, when the cooling rates are > 50°C/s, the mechanical properties remain very constant for 7050 alloy, and this behavior supports the recognized fact that 7050 is not a quench sensitive material. The yield strength change over the wide cooling rate range was ~ 40 MPa (or ~ 5800 psi).

Early in the quench the yield strength of the alloy is very low. Thus, yielding results from high

[1]G.W. Kuhlman and E.D. Seaton, "Enhanced Machining Performance of Aluminum Forged Products,"Metal Heat Treating, January/February, 1996.

stresses induced from significant thermal gradients from the surface to the center of the part during the early stages, and the largest change in the yield strength occurs during this period of cooling when the mechanical properties change the fastest. Non uniform yielding due to thermally induced stress levels leads to high residual stresses in the final part, and distortion upon machining. A good immersion quenchant for aluminum alloys should have a low thermal flux in the early stages of quenching between 400 - 200°C and a significantly larger thermal flux at surface temperatures are > 200°C.

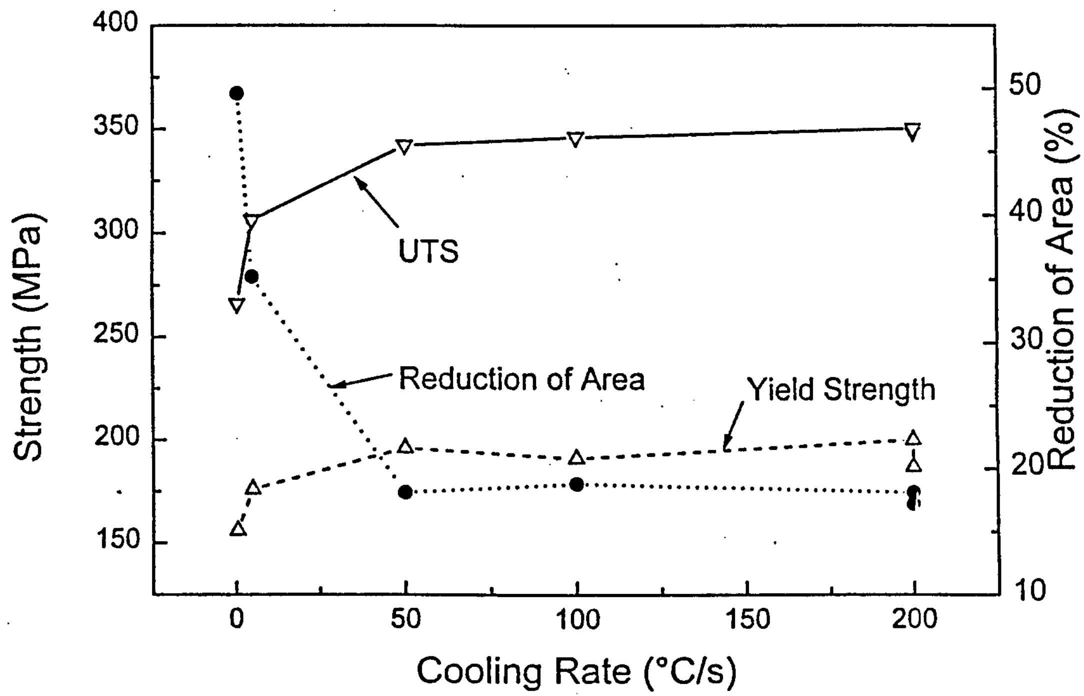

Figure 3 Mechanical Properties of Aluminum Alloy 7050 as a Function of the Cooling Rate

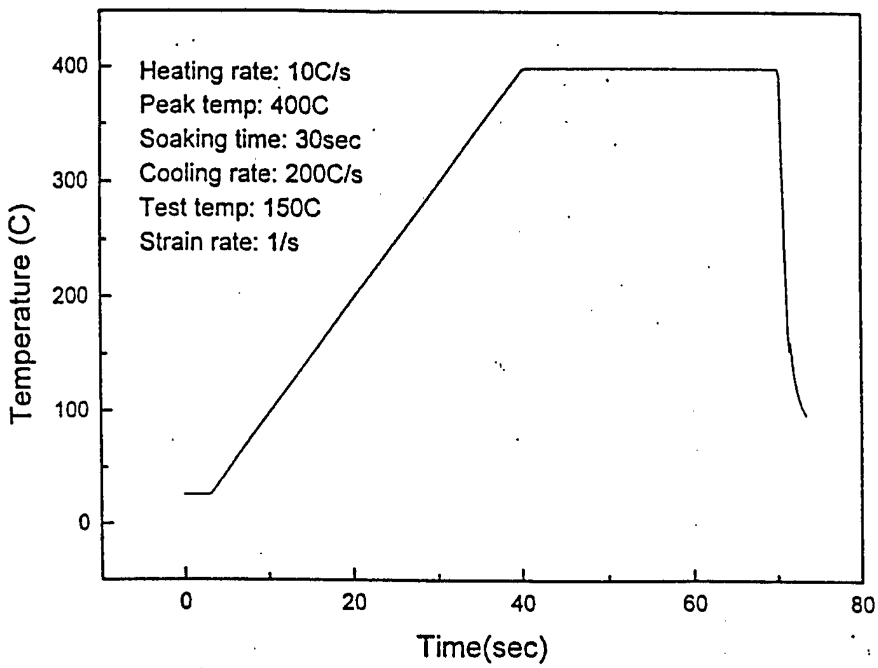

Figure 4 Typical Temperature as a Function of Time Curve

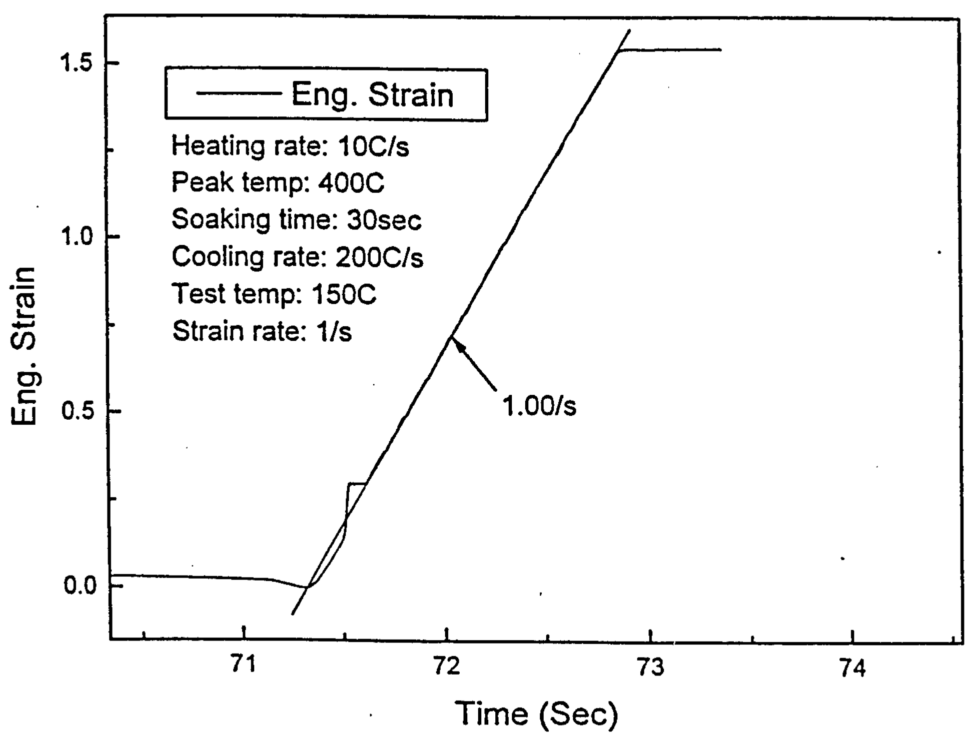

Figure 5 Gleeble Engineering Stress - Strain Curve for Aluminum Alloy 7050

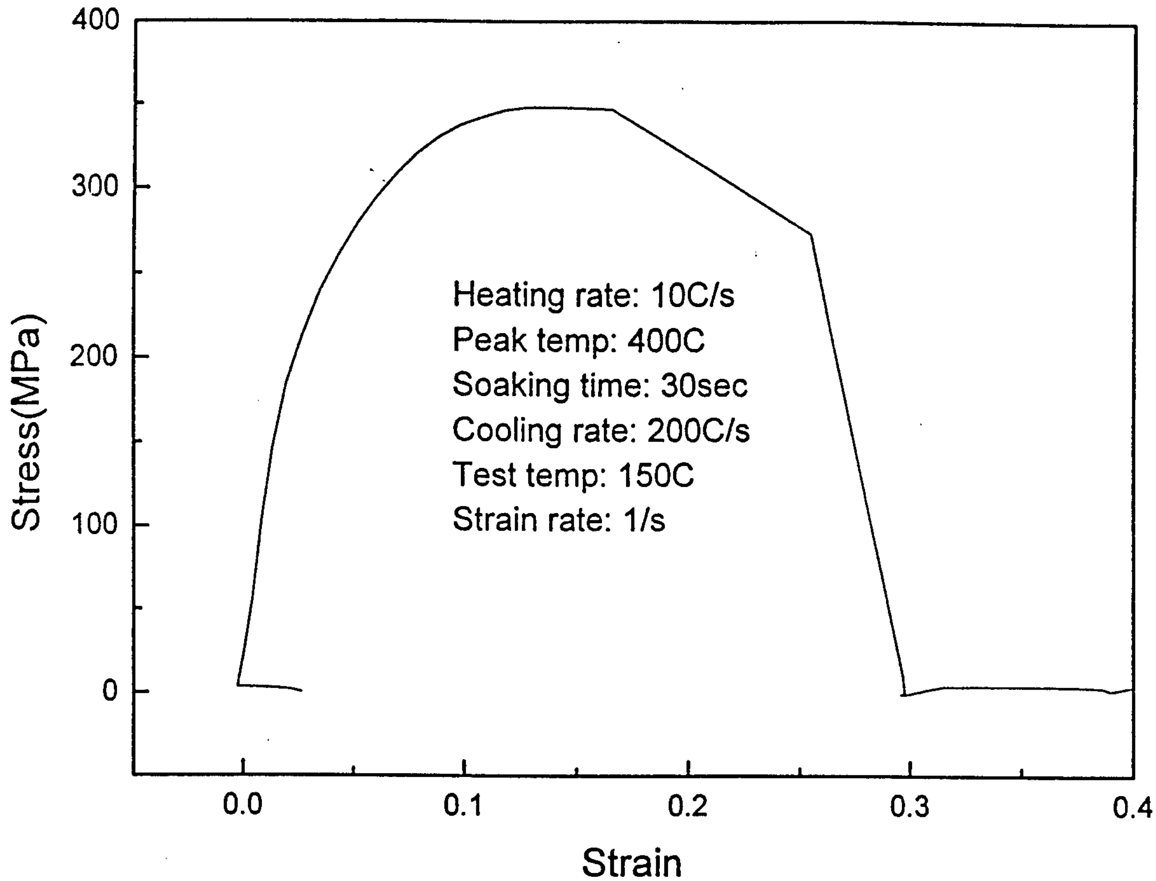

Figure 6 Strain as a Function of Time for a Typical Tensile Test

Task IV **Determination of Surface Heat Transfer Coefficients:** This task is aimed at developing an efficient and comprehensive estimate of the convection heat transfer coefficient *h*. This task is being done by Ohio University and UES Software, Inc. in collaboration with the NCMS Heat Transfer project. One part of this task involves developing rules for designing a family of probes based on a component's part family. These rules naturally involve a shape complexity factor consisting of a volume to surface area ratio and important geometrical features. The second part involves developing a robust 3D inverse FEA application for determining the surface heat transfer coefficients for the part, which is being quenched by some liquid medium such as water, oil and salt. During this effort, different numerical methods were studied and evaluated for their ability to calculate *h-values* for 3D shapes. The NCMS Heat Treatment project provided a set of data for a gear blank for evaluating an Inverse FEA

application, which is available as a module in the ProCAST™ software system. A description of the theory for the FEA application is subsequently given.

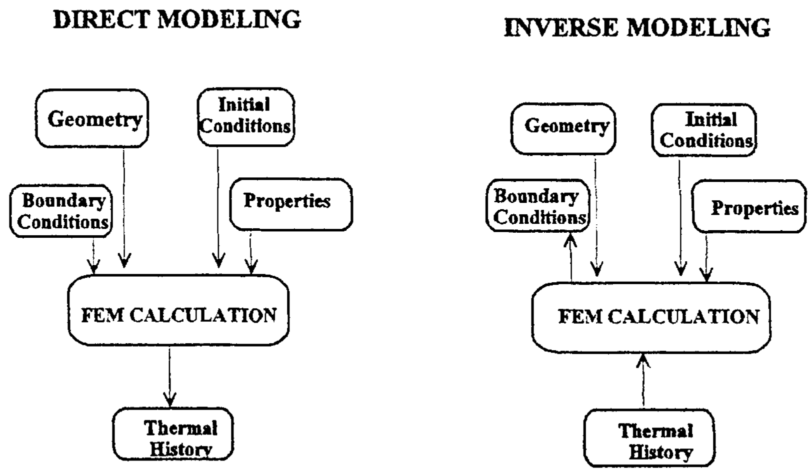

Figure 7 Comparison of Direct and Inverse Numerical Methods

<u>Application of Inverse FEA to the Estimation of Boundary Conditions</u>

One of the all-important difficulties associated with numerical simulation of thermal processes such as quenching and solidification is the lack of thermophysical properties and boundary conditions. However, using temperature measurements made under well-defined conditions, numerical simulation can be used to derive these missing data. The methods used for deducing the thermophysical properties and boundary conditions are called *inverse methods.* The schematic diagram compares the differences between the direct and inverse numerical methods. Simply stated, the direct numerical method calculates the thermal history knowing the boundary conditions and thermophysical properties, and the inverse method inputs the thermal history and the inverse methods derive the unknown thermophysical properties or boundary conditions.

The basic idea of the inverse method is equivalent to a standard least-squares method in which the analytical function is replaced by the numerical solution obtained from a *direct* FEM

calculation. A regularization method (Beck and Arnold, 1977; Beck *et al., 1985)* has been devised for deriving time-dependent boundary conditions, because these problems are ill-posed and can lead to instabilities if the time steps are too small. To determine the thermophysical parameters, e.g., thermal conductivity, specific heat, the least squares method has been modified to include a *maximum a posteriori (MAP)* algorithm.

Theory

Consider a domain, Ω, within which the heat flow equation has to be solved. This domain includes the component and the surrounding medium. A set of N_m thermocouples is placed at well defined positions, $\mathbf{x}_j$ (j = 1, N_m), within this domain to measure the temperatures as a function of position and time, i.e., T^m_{ij} at a certain number of times, t_i (i = 1, N_m). These measured temperatures are used to deduce a set of N_β parameters $\{\beta = \beta_1, \beta_2, \beta_3, \ldots, \beta_{N\beta}\}$ via a minimization of the function:

$$S(\beta) = \sum_{i=1}^{N_t} \sum_{j=1}^{N_m} \frac{1}{\sigma_T^2}[T^m_{ij} - T^c_{ij}(\beta)]^2 + \sum_{k=1}^{N_\beta} \frac{1}{\sigma_k^2}[\beta_k - \beta^0_k]^2 \tag{1}$$

where $T^c_{ij}(\beta)$ are the calculated temperatures at time t_i and position $\mathbf{x}_j$. The standard deviation, σ_T, is a typical error associated with the temperature measurement, whereas σ_k is a typical interval within which each of the parameters β_k is allowed to vary around an *a priori* (i.e., guessed) parameter, β^0_k. The MAP algorithm resumes to the standard least squares method

when the σ_k's are set to infinity. On the other hand, a parameter β_k will be fixed to the guessed parameter β_k^0, if the corresponding deviation, σ_k, is made very small.

The β parameters can be adjusted as follows:

- Tabulated thermophysical properties — For example, $\beta = \{k_1, k_2, \ldots, k_{N\beta}\}$, where the k_k's are the values of the thermal conductivities of the medium at some tabulated temperatures, T_k. The values of k in each interval, $[T_k, T_{k+1}]$, are linearly interpolated.

- Coefficients of a temperature-dependent thermophysical property function — For example, $k = \beta_1 + \beta_2 T + \beta_3 T^2 + \ldots + \beta_{N\beta} T^{N_{\beta-1}}$.

- Time-dependent boundary conditions at a given boundary — For example, $\beta = \{Q_1, Q_2, \ldots Q_{N_\beta}\}$, where the Q_k's are the values of the heat flow leaving a given boundary at tabulated times, t_k.

In the ProCAST implementation, no distinction is made between time- and temperature-dependent boundary conditions, assuming that the tabulated times, t_k, are much more spaced than the times used in the direct heat flow computations. This is equivalent to regularization. However, if the indices, k, of the tabulated heat flow are identical to the time steps, i, used for the direct computations, a different procedure can be used: the summation over the time steps in equation (1) can be eliminated and the heat flow at any future time step, Q_{i+1}, is then calculated from the temperature variations measured between (i) and (i+1) (Imwinkelreid and Rappaz, 1992).

The minimization of equation (1) is done as follows:

$$\frac{\partial S}{\partial \beta_i} = \sum_{i=1}^{N_t} \sum_{j=1}^{N_m} \frac{-2}{\sigma_T^2} [T_{ij}^m - T_{ij}^c(\beta)] X_{ijl} + \frac{2}{\sigma_l^2} [\beta_l - \beta_l^0] = 0 \qquad (2)$$

where X_{ijl} is the *sensitivity coefficient*:

$$X_{ijl} = \frac{\partial T_{ij}^c(\beta)}{\partial \beta_l} \cong \frac{T_{ij}^c\left(\beta_1 + \delta\beta_1, \ldots, \beta_{N\beta}\right) - T_{ij}^c\left(\beta_1, \ldots, \beta_1, \ldots \beta_{N\beta}\right)}{\delta \beta_l} \qquad (3)$$

$\delta\beta_1$ is an *a priori* variation of the parameter β_1, which is used to calculate the sensitivity coefficients. An iterative procedure is used to find the solution β that minimizes S(β). The calculated temperatures, $T_{ij}^c(\beta^{\nu+1})$, at the next iteration $\nu + 1$, are linearized also in this procedure:

$$T_{ij}^c\left(\beta^{\nu+1}\right) \cong T_{ij}^c\left(\beta^{\nu}\right) + \sum_{k=1}^{N_\beta} X_{ijk} \Delta \beta_k \qquad (4)$$

The increments, $\Delta\beta$, of the parameters are then found at each iteration as the solution of the set of linear equations:

$$[A]\Delta\beta = f \qquad \text{or} \qquad \sum_{k=1}^{N_\beta} X_{ijk} \Delta \beta_k = f_1 \qquad (5a)$$

with:

$$A_{lk} = \sum_{i=1}^{N_t} \sum_{j=1}^{N_m} \frac{X_{ijk} X_{ijl}}{\sigma_T^2} + \frac{\delta_{lk}}{\sigma_T^2} \qquad (5b)$$

$$f_l = \sum_{i=1}^{N_t} \sum_{j=1}^{N_m} \frac{1}{\sigma_T^2} \left[T_{ij}^m - T_{ij}^c(\beta^v) \right] X_{ijl} - \frac{\beta_l^v - \beta_l^0}{\sigma_l^2} \tag{5c}$$

and δ_{lk} is the Kroneker delta symbol.

The implementation of the MAP inverse method (equations 5) can be done in a direct program that calculates $T_{ij}^c(\beta)$ once the parameters, β, are known. From guessed initial values of $\beta^{(v=0)}$, the temperatures $T_{ij}^c(\beta^v)$ and sensitivity coefficients X_{ijl}, equation (3), are calculated at each iteration υ. Knowing these values, equations (5) are solved to obtain the increments $\Delta\beta$ until convergence is reached. Within each iteration, the direct code solves $N_{\beta+1}$ direct problems. This requirement might be especially CPU-intensive if: (a) the problem is three dimensional, (b) the number of parameters N_β is large, and (c) the convergence is slow. This problem is less critical in two dimensional problems. The MAP algorithm has been implemented in the ProCAST FEA integrated application as a module and calls its direct heat flow module as a subroutine.

Inverse Analysis of Test Data on Gear Blank

The test data for this analysis was provided by Mr. Douglas Schick, Torrington/Ingersoll-Rand, Advanced Technology Center, Torrington, CT. Mr. Schick is chairperson of the NCMS Collaborative Heat Treatment Project Team, which served as the Industrial Advisory Board for this SBIR project. The results of our analysis are summarized by a series of attached figures.

Our mode of solution consists of selecting important points, which are called *key points* in the test data, where the heat transfer mode is expected to change. This change would be manifested as a knee or bend on the *h*-curve. The inverse code is programed to solve for the heat transfer coefficient with these *key points*. The heat transfer coefficient *h* is assumed to vary linearly in between these points. The shape of the function *h* will become smoother as more *key points* are selected.

Once the *h* function is obtained, the corresponding numerical solution from the direct simulation is compared with the experimental data to determine the accuracy of the solution. It can be seen that the two curves agree very well, and the simulation result smooths the sinusoidal variation of the temperature data. It should be noted that temperature data from two equivalently placed thermocouples were averaged to get each of the experimental curves.

The simulation results are compared to experimental data in Figures (8) to (13) for different pairs of equivalently placed thermocouples. Each of these results clearly shows that the temperature as a function of time curves produced by direct simulation compares very well with the actual thermocouple data obtained at a specific position $\mathbf{x}_j$ for the tabulated times t_k. The time-dependent *h* function is shown also on these figures.

A comparison of the heat transfer coefficients for a different number of *key points* for a set of averaged temperatures T_k is shown in Figure (13). It can be seen that the results for *h* agree very well for the two cases with different number of *key points*. Table 1 shows the results of the inverse code for a run using six *key points* and ten *key points*, respectively.

The heat transfer coefficients for the two cases compare very well. We conclude from these tests that the inverse code is capable of providing thermophysical properties, temperature-dependent boundary conditions at a given boundary, and time-dependent boundary conditions at a given boundary. The research has demonstrated that a direct FEM heat-flow code can be used in an inverse way to deduce the boundary conditions and/or thermophysical properties.

Table 1 Results of Inverse Code Analysis for the Heat Transfer Coefficient *h* Comparing the Use of Six and Ten Key Points			
h **(watts/m²K) - Six Key Points**		***h*** **(watts/m²K) - Ten Key Points**	
time - seconds	*h*	time - seconds	*h*
1.0	45.24	1.0	43.33
7.0		7.0	110.49
8.0	119.81	8.0	143.54
8.2		8.2	1251.37
8.5	3373.98	8.5	2985.26
9.0	4969.26	9.0	4918.30
10.0		10.0	4230.90
11.0	3351.17	11.0	3372.04
12.0		12.0	2878.43
16.0	868.93	16.0	892.91

Three-dimensional problems can become CPU intensive because of the large number of direct calculations that have to be made. If N_β parameters have to be determined, the inverse calculation is then equivalent to $N_{\beta+1}$ direct calculations in each of the iterations made to find a solution. Therefore, the CPU time associated with such inverse calculations may limit the geometrical complexity of the problem. This fundamental problem was investigated by considering the use of a probe, which was designed to have only the crucial geometrical features of the component and its thermal characteristics. Experiments also showed that if accurate experimental measurements can be made of the temperature as a function of position and time, accurate values of the thermophysical properties and boundary conditions can be reasonably well predicted in heat-treatment processes without an excessive amount of CPU time.

One-dimensional experiments with precise knowledge of the boundary conditions are most preferable for the determination of thermophysical properties. On the other hand, boundary

conditions can be reasonably well predicted for complex shapes during quenching if the thermophysical properties are known.

Application of the Inverse Method to determine Surface Heat Transfer Coefficients

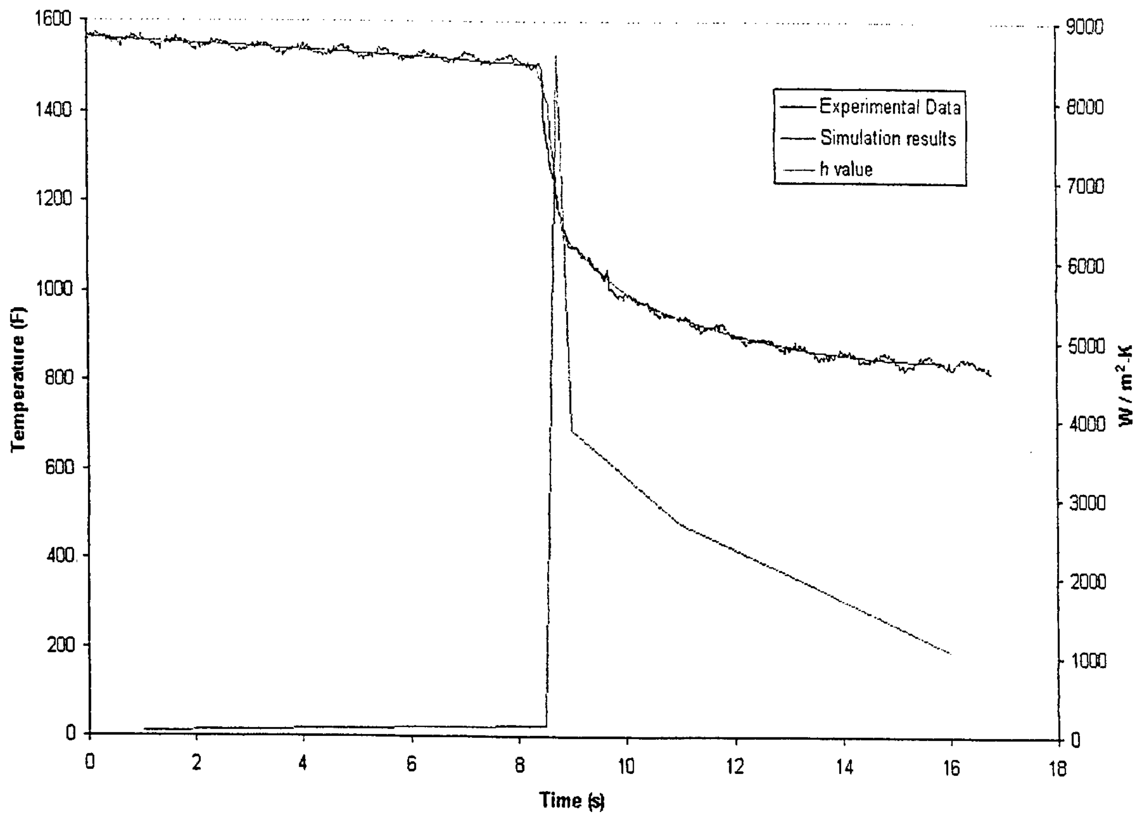

Figure 8 Experimental Determination of Surface Heat Transfer Coefficient

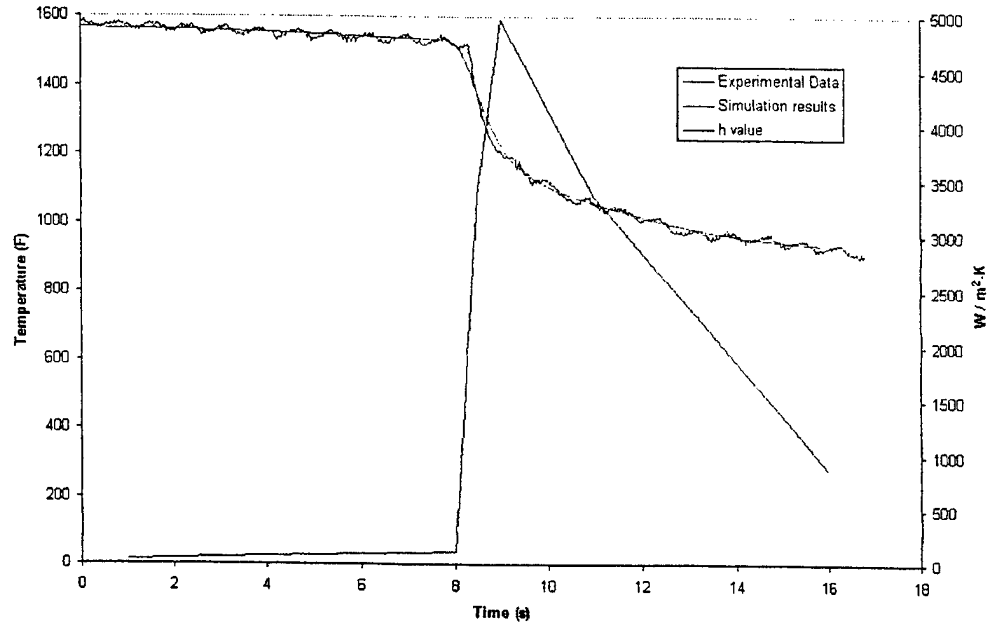

Figure 9 Experimental Determination of Surface Heat Transfer Coefficient

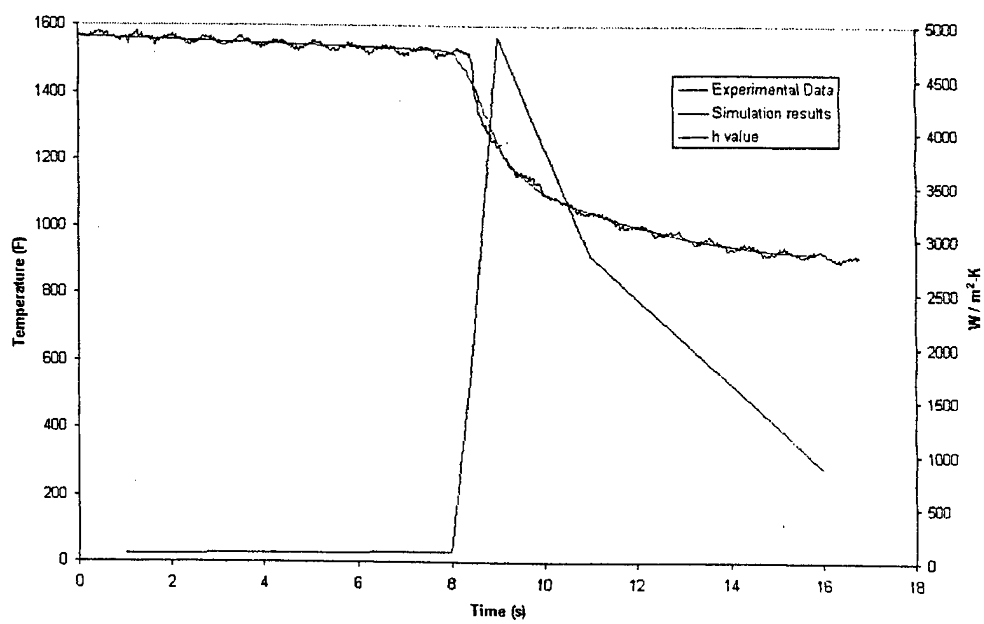

Figure 10 Experimental Determination of Surface Heat Transfer Coefficient

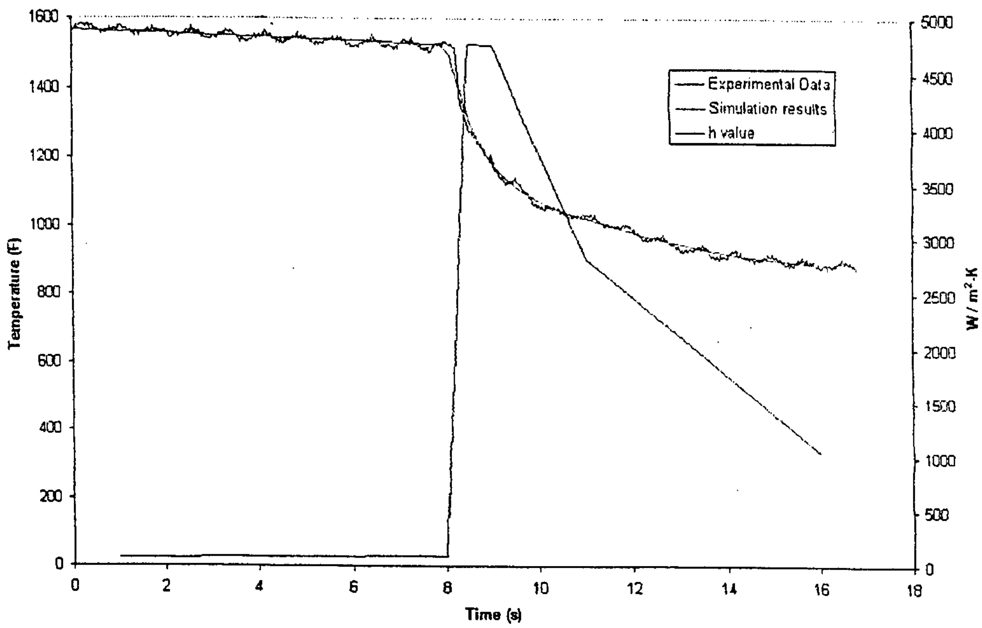

Figure 11 Experimental Determination of Surface Heat Transfer Coefficient

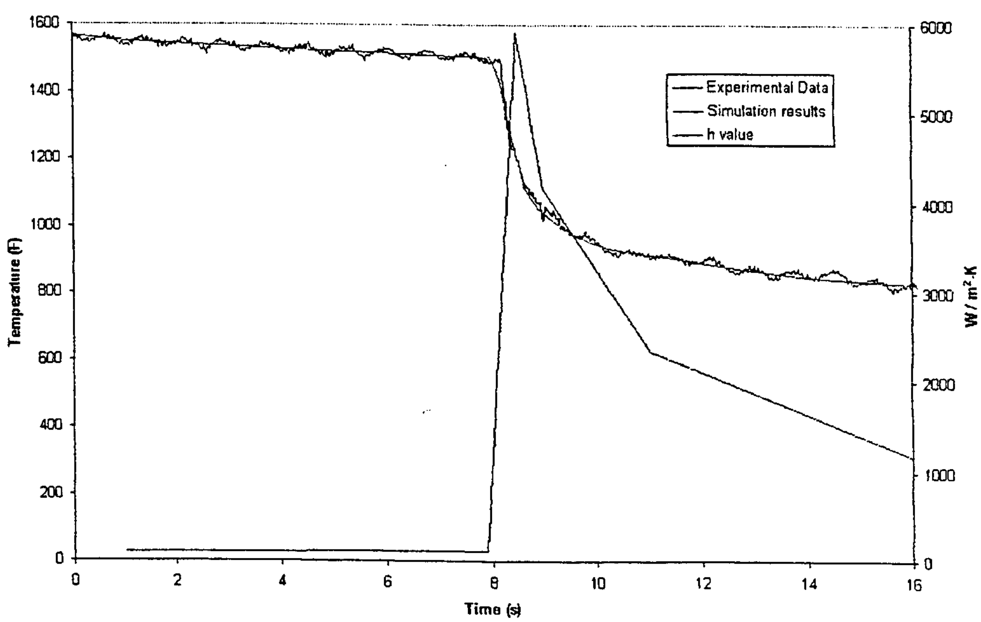

Figure 12 Experimental Determination of Surface Heat Transfer Coefficient

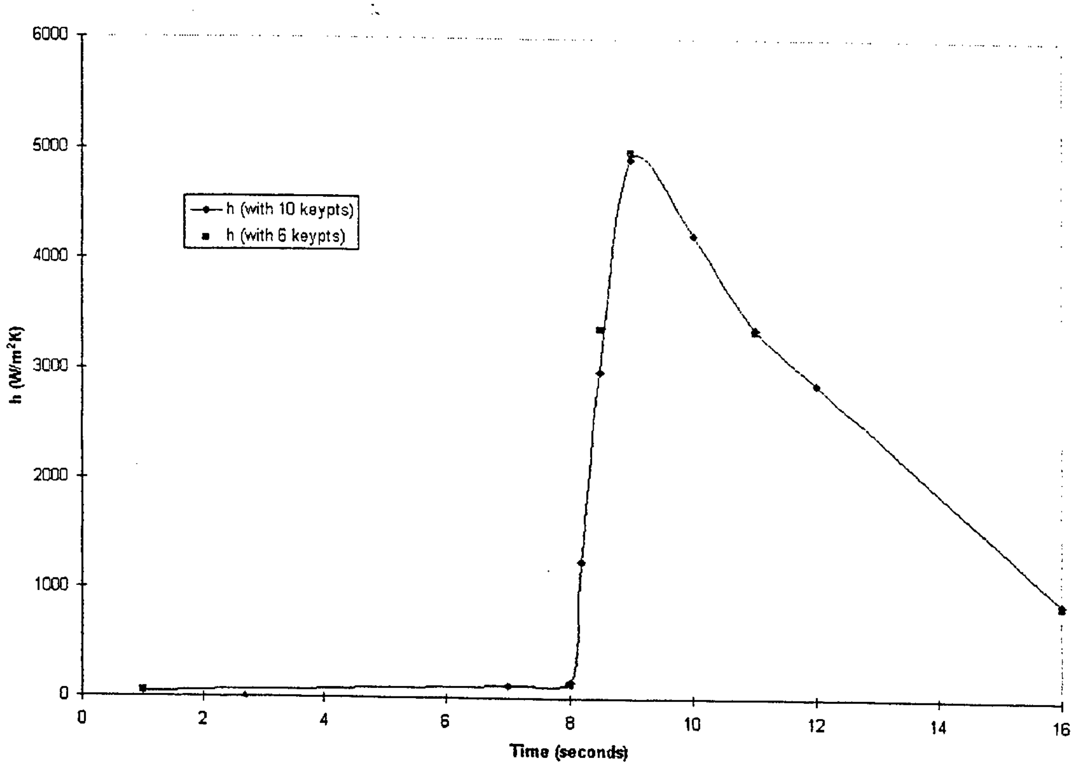

Figure 13 The Relationship of the Number of Key Points with the accuracy of the *h*-*value*

Collaboration with the NCMS Heat Treatment project provided the high quality experimental data of temperature as a function of time and position, which is needed for testing the capability of the inverse FEM application for determining the surface heat transfer coefficients and the thermophysical properties of material systems. The results of this testing showed that the inverse application does give good results.

However, it was noted in the discussion that the FEM inverse method can be CPU time limited for complex three-dimensional problems, due to the large number of direct solution calculations that may be needed in each iteration of the solution. The Phase I research investigated another

approach for handling complex three-dimensional geometries. The next section will discuss the possibility of using a family of thermal probes for overcoming the computational barrier using conventional engineering workstations or personal computers.

Determination of Heat Transfer Coefficients Using Part Family Thermal Probes

Quenching is a process that is often connected to metal forming processes. Forged parts are sometimes quenched out of the finisher dies, and, at other times, forged or cast netshape parts may be solution heat treated and aged to obtain the strength properties that the designer wants. Quenching is a complex heat transfer process that must be controlled to assure the formation of the desired transformation products, while, at the same time, providing optimal control of distortion, residual stresses and cracking (Kuhlman and Seaton, 1996; Nicol et al., 1996; Fletcher, 1989). To optimize the quenching process, it is not only important to select the proper quenchant with respect to alloy and required cross-section being heat treated, it is also critically important to properly design the quenching system to assure optimal uniformity of heat transfer during quenching to minimize the formation of undesirable thermal gradients both within the metal and across the cooling surface.

It is very difficult to develop a data base for doing linked or connected simulations that cover all possible thermal treatment possibilities. Therefore, the Phase I research was also aimed at developing a more efficient and comprehensive estimate of convection heat transfer coefficient h by a combination of fundamental analysis and experimentation. The objective of this research is to develop a practical and reliable method for generating heat transfer coefficients during quenching and using it in design. The focus has been on the fundamental issues of quenching to develop a thermal probe for industrial use. The goals of this subtask are the following:

- Use analytical solutions to design the probe and solve the inverse heat conductivity problem
- Develop a robust probe to perform experiments that determine the temperature as a function of time, position and geometrical features

- Demonstrate feasibility for using part family probes and analytical solutions to determine surface heat transfer coefficients.

Although most investigators of quenching (Totten *et al.*, 1994) focus on the convective heat transfer equation $q = h(T_s, T_e)$ as the only basis for analysis of quenching, this equation cannot represent a complete picture of the process without the conduction heat transfer in the solid part. The conduction heat transfer equation is $\alpha^2 T = \frac{1}{\alpha}\left(\frac{\partial T}{\partial t}\right)$, where α is the thermal diffusivity of the solid part. These two equations for conduction and convection produce a temperature profile on the part being quenched. Therefore, both of these governing equations should be considered in the design and analysis of the quenching process. The interaction of the different stages of the quenching process is related to the interaction between the conduction heat transfer inside the solid and transfer from the solid boundary to the liquid. It can be shown that the analysis of the above two equations provide information on "characteristic internal and external cooling times." The internal cooling time is related to the geometry and thermal properties of the solid only, and it is indicative of the cooling rate within the solid, whereas the external cooling times are based on the cooling process at the solid-liquid interface. For a part that has a characteristic dimension L and thermal conductivity k, the characteristic cooling times are dependent on the Fourier number, $F_o = \frac{\alpha T}{L^2}$, and the Biot number, $B_i = \frac{hL}{k}$, for the process.

As an example, the vapor blanket stage during quenching is accompanied by low Biot numbers, indicating that the internal cooling times are longer and comparable to the external cooling times. This produces lower temperature gradients in the solid.

In designing the probe and the analytical solution, the governing equation for heat transfer in a simple plate being quenched by liquid on one side is the starting point:

$$\frac{\partial T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{6}$$

$$T(x,0) = T_o \tag{7}$$

$$\frac{\partial T}{\partial x} = 0 \tag{8}$$

$$k\frac{\partial T}{\partial x} = q \tag{9}$$

The initial condition is a constant temperature T_o

The boundary conditions to be used are as follows:

At $x = 0$

At $x = L$

where

k = thermal conductivity

q = heat flux, $q = h(T_s - T_e)$

T = temperature

h = convective heat transfer coefficient

t = time

x = space coordinate

L = thickness of the plate

It can be shown that the general temperature profile is given as an infinite series:

$$T(x,t) = T_o + \frac{qL}{12k} + \frac{q}{kL^2}\left(x^3 - Lx^2\right) - \sum_n \frac{2qL\left(12-\pi^2\right)}{k\pi^4}\cos\left(\frac{\pi}{L}x\right)\exp\left[-\alpha\left[\frac{\pi}{L}\right]^2 t\right]$$
$$- \ldots - \frac{2qL\left(2^2\pi^2\right)}{n^4 k\pi^4}\cos\left(\frac{2\pi}{L}x\right)\exp\left(-\alpha\left(\frac{2\pi}{L}\right)^2 t\right) + \ldots.$$

The above solution is a function of the Fourier and Biot numbers (Loshkaroev, 1994). In designing a probe, care must be taken that these two dimensionless numbers match the component for which the heat transfer coefficient is being sought. For greatest applicability to the industrial process, the probe design, i.e., geometrical features, must be sufficiently flexible that the temperature history is typical of the actual component. Similarly, the probe geometry should be simple enough so that an efficient solution procedure can be adopted. Experience gained on this Phase I project suggests that a family of probes may be necessary to handle components in the same part family.

The analytical solution provides insight into the development of the inverse heat transfer coefficient probe (IHCP) code. Almost all inverse codes are computationally intensive as explained previously, and this is particularly true for complex geometries. Inverse codes use multiple runs of the direct solution (Barnea *et al.*, 1994) to converge to a solution. However, if part of the geometry can be simplified without sacrificing accuracy, the IHCP solution can be made significantly more efficient for the following reasons:

- A simpler geometry is solved much more easily and faster than a complex geometry.
- The analytical solution can be used to make a very intelligent guess to speed up the convergence of the direct solution within the inverse code.

The inverse code being designed in this Phase I project will use the analytical solution to converge to a numerical solution much faster than conventional methods. It became obvious during the course of this research that this approach can make inverse methods highly efficient and more amenable to industrial use.

Experimental Probe and Trial Experiments

A probe was designed as a relatively large rectangular box made of 304 stainless steel plates 0.25 inch in thickness with dimensions of 6 inches x 4 inches, and this configuration is shown in Figure (14).

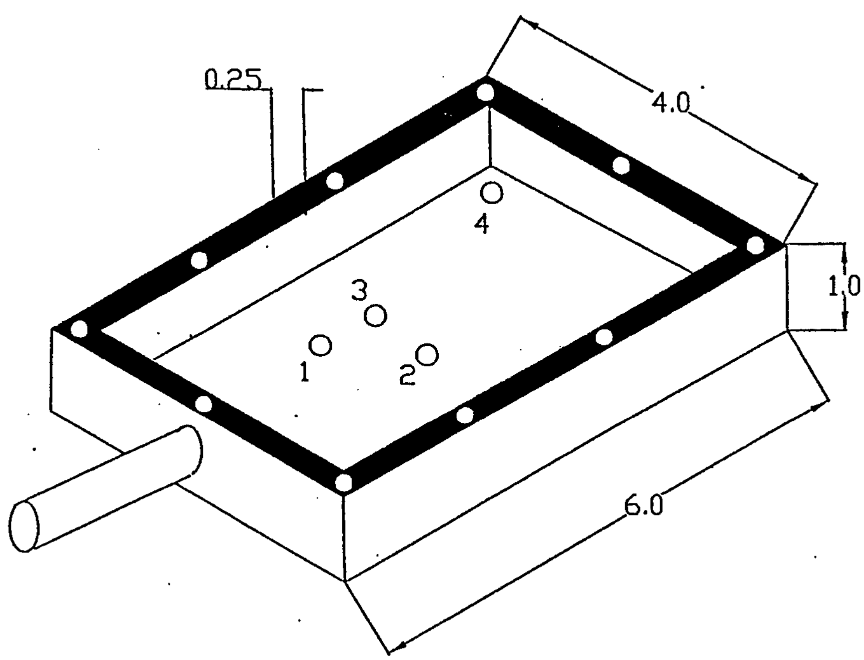

Figure 14 304 Stainless Steel Probe Showing Four Thermocouple Positions: All dimensions are in inches

This probe is unlike traditional probes (El Genk and Gao, 1996; Huang *et al.*, 1994), which are small and cylindrical. This probe was made of 304 stainless steel to avoid complications due to phase transformations that could occur during experiments with other alloy compositions. A rectangular plate is used as a lid to cover this box, and it is attached by 14 screws. This design allows the probe to be easily opened for examination and to modify experimental parameters. A thin copper gasket is used between the probe box and the lid to avoid the leakage of quenchant into the probe. Water was used as the quenchant in these experiments.

Four type-K chromel-alumel thermocouples were used to monitor temperature, and they were silver soldered to the inner surface of the probe at four different locations. Thermocouple #3 was soldered to the inner surface at the geometric center. Thermocouples #1 and #2 was soldered to the inner surface away from the center. The location of the thermocouples are shown in Figure (14). Thermocouples #1 and #2 are used to cross check the data provided by thermocouple #3 to make certain that the heat transfer is one-dimensional. Thermocouple #4 was soldered to the inner corner to monitor the temperature history at the corner.

A circular hole of 0.5 inch diameter was made on one of the thinner sides, and a 304 stainless steel pipe 0.5 inch in O.D. was welded to it. This was used as a conduit for the thermocouples to be brought out of the probe for connection to the data acquisition system.

<u>Data Acquisition System (DAS)</u>

The stainless steel probe is connected to a data acquisition system shown in Figure (15). The data acquisition system consists of a DAS 1701 ST board manufactured by Keithley Metrabyte, which has a provision for measuring 16 single ended or eight differential channels with a 12 bit resolution and a capacity of measuring 166.67 kilo-samples/second; each channel has gains of 1, 5, 50 and 250, respectively. An EXP 1800 accessory board is used with the DAS 1701 ST board to increase the gain to 400 and to make the Data Acquisition System more accurate.

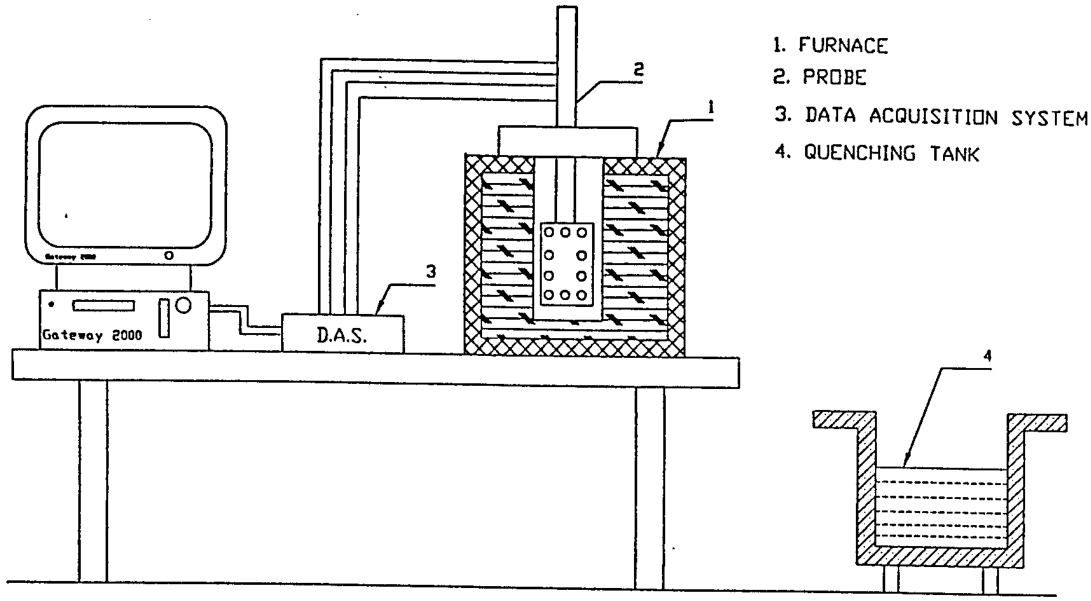

Figure 15 Experimental Setup Showing the Furnace, Probe, DAS and Quenching Tank

<u>Experimental Procedure and Results</u>

The experimental procedure consists of the following steps:

- The probe lid is sealed and thermocouples are connected to the DAS.
- The probe is heated to the specified temperature (350 C to 450 C).
- The DAS initialized to collect and display the sampled data.
- The heated probe is quenched in water.
- The data is collected and analyzed.

The surfaces of the quenching probe were thoroughly scrubbed with a wire brush to remove any foreign materials, and the connections leading from the interior thermocouples of the quenching probe to the data acquisition system were carefully checked to ensure all connections were proper. The quenching probe was then carefully placed adjacent to the control thermocouple inside the muffle furnace. Control parameter values for the furnace temperature controller are adjusted to guarantee that the furnace reaches the desired steady-state temperature in a stable manner.

Two data acquisition programs are used. The first program is used to monitor the probe's thermocouple readings while the probe is being heated to the desired temperature, which was typically 400 C. A second program was used to collect the temperature data from all the thermocouples during the quenching process. During the quenching process, a sampling rate of 100 Hz was used. Data acquisition for the cooling curve was initiated approximately one second before quenching. Each of the thermocouples was sampled at a rate of 0.01 seconds for two minutes. Therefore, 12,000 samples per channel were taken. The data acquisition applications used during these experiments were created with a software package called TestPoint™. Five Type K thermocouples with a gain of 250 was used in the data acquisition system. The fifth thermocouple is used to monitor the external surface of the probe.

During quenching of the probe, the thermocouple output, e.g., typically millivolts, are converted to temperatures and stored in data files. Figures 16 to 18 show the temperature history of the probe, which was quenched from initial temperatures of 350, 400 and 450 Celsius. These curves show that the temperature history is captured in detail, and the cooling curves are quite similar.

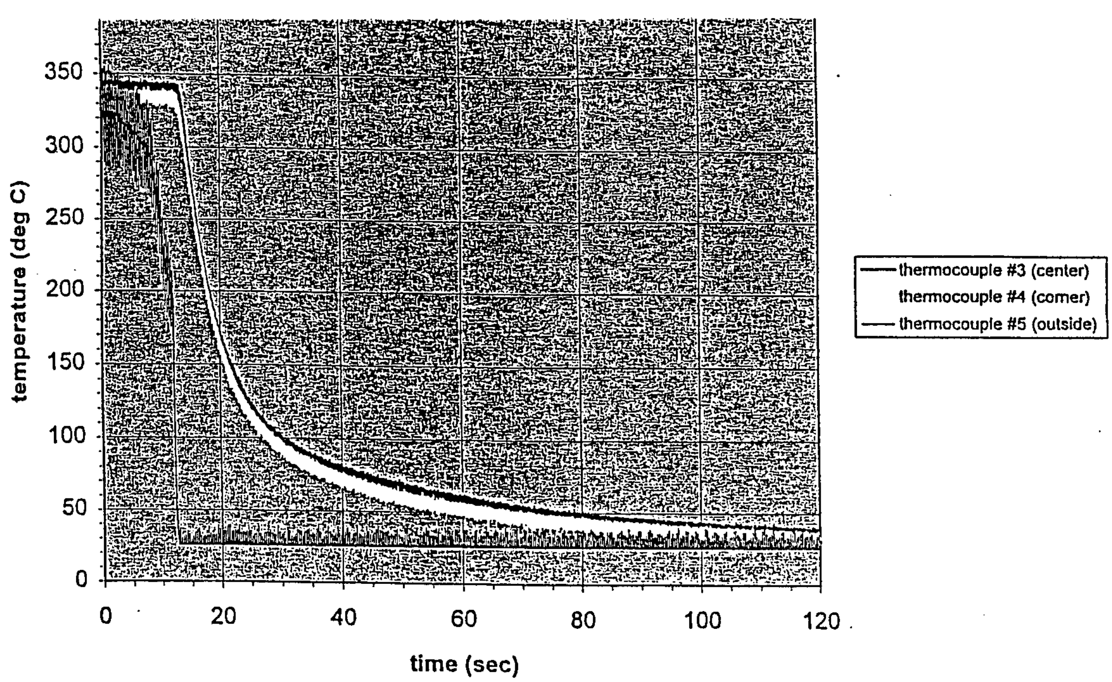

Figure 16 Cooling Curve for 304 Stainless Steel Probe from 350 C Furnace Temperature

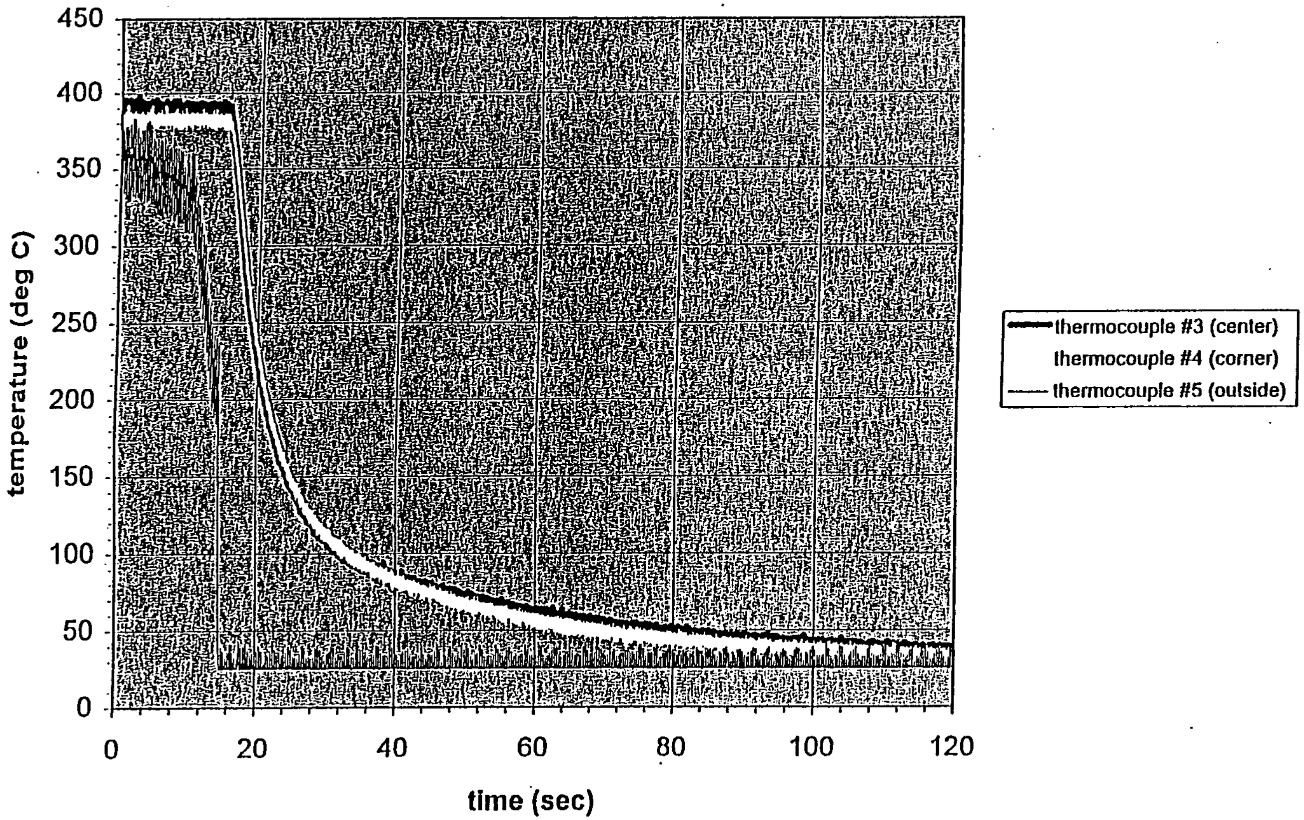

Figure 17 Cooling Curve for 304 Stainless Steel Probe Quenched from 400 C Furnace Temperature

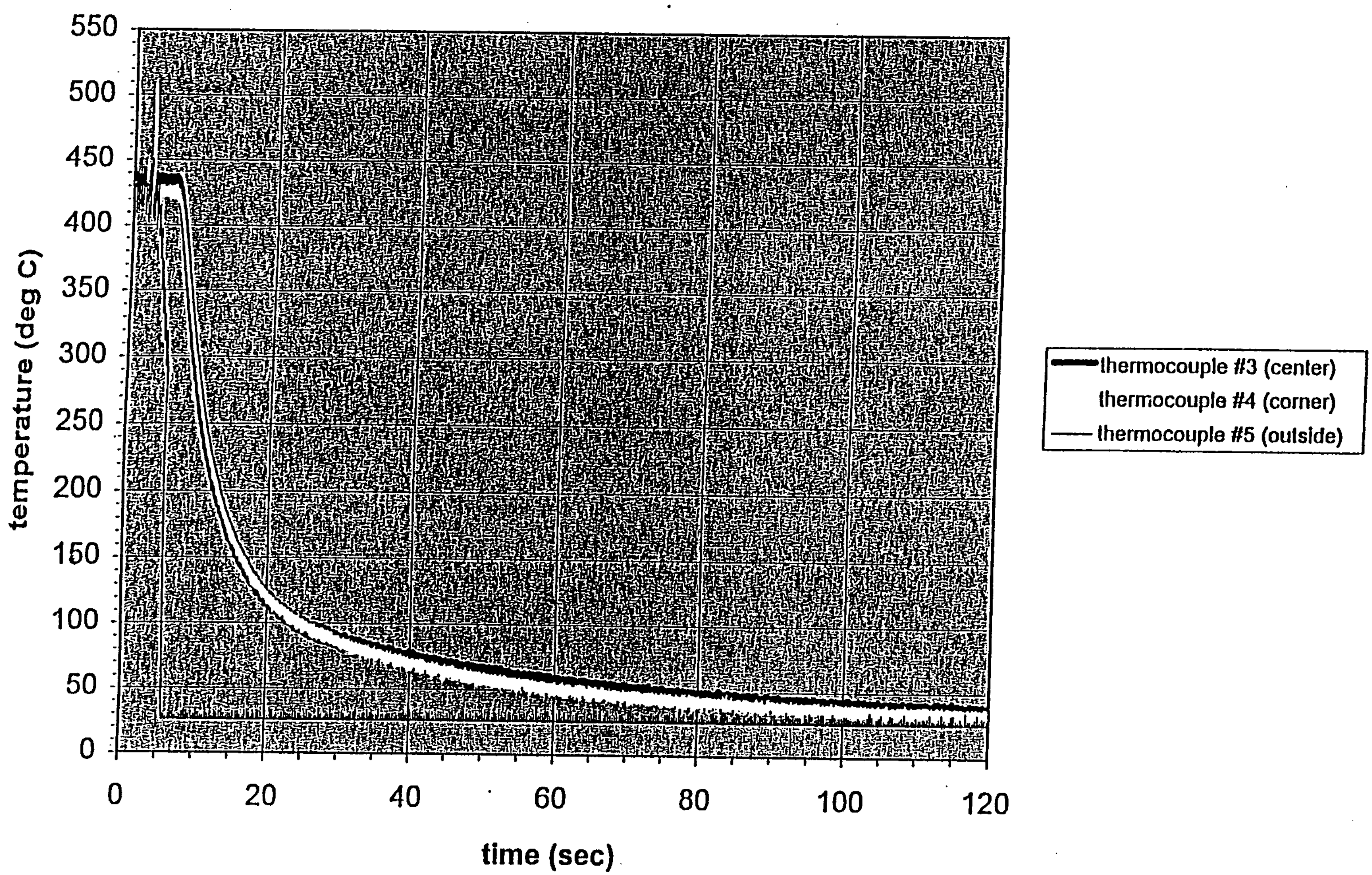

Figure 18 Cooling Curve for 304 Stainless Steel Probe Quenched from450 C Furnace Temperature

Development of an Inverse Code and Probe

A simple inverse finite element code was written. The code was designed to be used with the probe, which was described above. This code is unique in that it incorporates analytical solutions as part of the solution process. The analytical solutions are used with a numerical algorithm to provide the heat transfer rates during cooling. The experimental studies performed at Ohio University show that this code has promise for speeding up inverse calculations.

The Phase I research has shown that the approach to probe design is successful. Additional work needs to be carried out to complete the probe design and improve the experiment. Future design work will incorporate geometric features such as gear teeth, different surface finish and materials such as 7050 aluminum alloy for the probe. Fast response thermocouples will be incorporated into the experiment. For thicker sections, multiple thermocouples will be used at different depths.

The probe holder will be modified so that the probe can be immersed into the quenchant at different angles relative to the vertical axis. Different types of quenching media will be investigated also, and the effect of agitation of the quenchant will be examined.

Feasibility was demonstrated in Task IV for developing a family of probes for determining the surface heat transfer coefficient very efficiently and in a robust manner. Each part family will have its own unique probe design, and this will allow the surface heat transfer coefficients for complex geometries to be determined without an excessive amount of computing time. The commercially available inverse code module in the ProCAST™ finite application was found to give good solutions. This inverse module represents state of the art software for determining either the thermophysical properties of the material or the boundary conditions of a solidification or quenching process.

DISCUSSION

Manufacturing is the backbone of the United States economy, and it is also the backbone of sustainment and affordable defense products with world class quality. Manufacturing operations require a continual infusion of the newest information, process design and control technologies to maintain global ability to reliably deliver products that best serve the customer at the lowest cost. The agility and economy, which can be provided by new integrated design and control systems, must be exploited to improve the competitiveness of U. S. industries. Through the SBIR Team's work with the National Center for Manufacturing Science (NCMS) considerable evidence has been obtained that indicates industry is now willing to undertake challenges to implement a next generation design system for producing netshape components.

Today's dynamic market causes the forging industry to be faced with many challenges. The U. S. forging industry has downsized its operations from approximately 550 forging operations in 1986 to about 450 facilities in 1997. Total forging capacity has decreased 25 percent during the past decade with an accompanied loss of 16,000 production jobs. This industry, like the metal casting industry, is comprised almost entirely of small to medium sized enterprises (SME's), and the average employment of custom forging plants is less than 100 employees. This change reflects the change to custom forging plants, which dominate the industry. Such change is having an impact on the DOD's sustainment and affordability needs, since most current operations are designed for commodity parts.

One causal factor driving the industry shrinkage is the inability of custom forging suppliers to produce precision complex shapes economically from steel and high temperature alloys. The DOD and commercial aerospace and automotive business sectors want and need precision-forged parts. Precision forged parts[1] would reduce raw material requirements, minimize process

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[1] Precision forged parts have functional surfaces; are forged to pre-grind tolerances, and have shapes, which are two-dimensional and three-dimensional axisymmetrical and non axisymmetrical.

waste, and decrease energy cost and consumption, and environmental impact. Precision forged parts would have a longer life cycle performance. The lack of precision forging methodology and systems capability has resulted in precision components undergoing costly, time-consuming finish machining on rough forgings, creating tremendous waste problems and associated energy costs. A study published by the U. S. Department of Commerce[2] indicates that the custom forging plants allocate more than 90 percent of their sales revenue to direct materials, labor and energy costs. Without any downstream process optimization, it has been projected that a 35 percent conversion of the custom forging facilities to precision forging would produce a possible total forging process energy savings of 20 percent. This energy saving is considerable, since the annualized energy savings due to precision forging approaches one trillion British thermal units per year, which neglects additional energy savings due to integration of precision forging with other manufacturing functions and productivity enhancements in the manufacturing chain.

Industry envisions and wants three-dimensional (3D) engineering workstations for doing connected simulations, which link other processes in the manufacturing chain, and speeding up the design of structural forgings. This research investigated the possibility of linking the modeling of heating and cooling thermal processes with other processes such that it would be possible to design and produce machining-friendly forgings, and feasibility for this linkage was shown. This study also considered the feasibility of *reducing the cost of forged components by the industry goal of 25 percent* through the implementation of precision forging methodologies on an affordable PC Windows NT Workstation. The following table shows some of the benefits that may occur by developing an affordable precision forging methodology for the SME forging companies.

The long pole in the tents of precision forging and casting as well as for other netshape processes is die design. To overcome this precision forging challenge, a practitioner's knowledge base should be incorporated into the design system for novice designers to use through responsible agents.

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[2] National Security Assessment of the U. S. Forging Industry: A Report to the Department of Defense, U. S. Government Printing Office, December, 1992.

Table 2. Anticipated Benefits of Connected Simulation & Design	
Benefits	**How Achieved**
25% Reduction in Equipment Maintenance	Process Control, Pre-blocker and Preform Design, Process Understanding/Consistency
20% Reduction in Total Forging Energy Input	Equipartitioning of Input Energy Between Different Stages of Manufacturing Process, Total Process Understanding
Tenfold Increase in Die Life for Real Savings in Die System Cost	Pre-blocker and Preform Shape Optimization, Fail Safe Design Against Failure by Fatigue and Fracture; Reduced Forging Pressures; Increased Wear Resistance via Optimized Material Flow, Selecting Proper Lubricants, and Periodic NDI of Tooling
Reduced Input Material Costs & Requirement	Netshape Process Design, Flash Minimization, Process Control, Equipment Compliance
4:1 Reduction in Design Lapse Time	Workflow Management & Design Automation
10:1 Reduction in Engineering Labor	Process Understanding, Streamlining Information Flow, Easy Access to Design Knowledge, Integrated Software & Databases
Rapid Response to Today's Dynamic Market Demands	Agent-based Product and Process Design Methodologies, Simulation-based Design, and Business Practices
Affordable Access to Defense Critical Industrial Base Manufacturing Capability	Rapid Response Design & Manufacturing Methodologies/Technologies
Process Understanding That Reduces Risk	Manufacturing Process Maturity
Affordable Critical Components, Remanufacture Support and Design Feedback	Manufacturing Process Control and Improvement
Consistent Properties in Finished Product	Process Designed to Operate in Domain of Stable Energy Dissipation & Microstructure Evolution; Complete Set of Mechanical Properties, Thermophysical Properties and Process Boundary Conditions

The design process is very complex at the detail level of design, and studies reveal that 60 percent of the design lapse time is spent in this stage. An activity model of the forging and casting design processes is shown in figure (19), (Shende *et al.* 1994). This Global Design Methodology was implemented using the KI-Shell, which is frequently called *groupware, cooperative processing, concurrent engineering, integrated product/process development (IP/PD) or enterprise integration*. This shell delivers workflow technology across different platforms with process decision support systems. It manages connections needed to access data, applications, and systems in a business enterprise. The design methodologies embedded in integration shells deal with the core problems of design. It *couples designers* by managing connections between the customer and the part supplier companies. Designers have a difficult time to prioritize issues, because designers, depending on their experience and industry, do not have a common language for comparing the importance of issues. Thus, a decision support system is needed for resolving issues.

The Knowledge-based Integration Shell was used also to facilitate the development of a client-server environment. Data or application functions can be located at one or more servers, and users at client workstations can access data or application functions at those servers from geographically different locations. In addition, data and applications functions used in the workflow can reside on any platform, including host systems such as high performance computers. Applications can be accessed on multiple platforms from a single workstation without the user's knowledge of the characteristics of application startup. *This capability is needed because today's designers need to know how to use a mix of applications, especially if the design activity calls for connected simulations.* For example, to simulate a pressure die casting process, a ProCAST application might be started, but the user does not have to perform any special tasks to start the application. If the design task were to include doing optimization via simulation, a shell is definitely needed to take the tedium out of the process and free the designer to work on higher priority activities. The user just starts the particular task in the particular shell's framework.

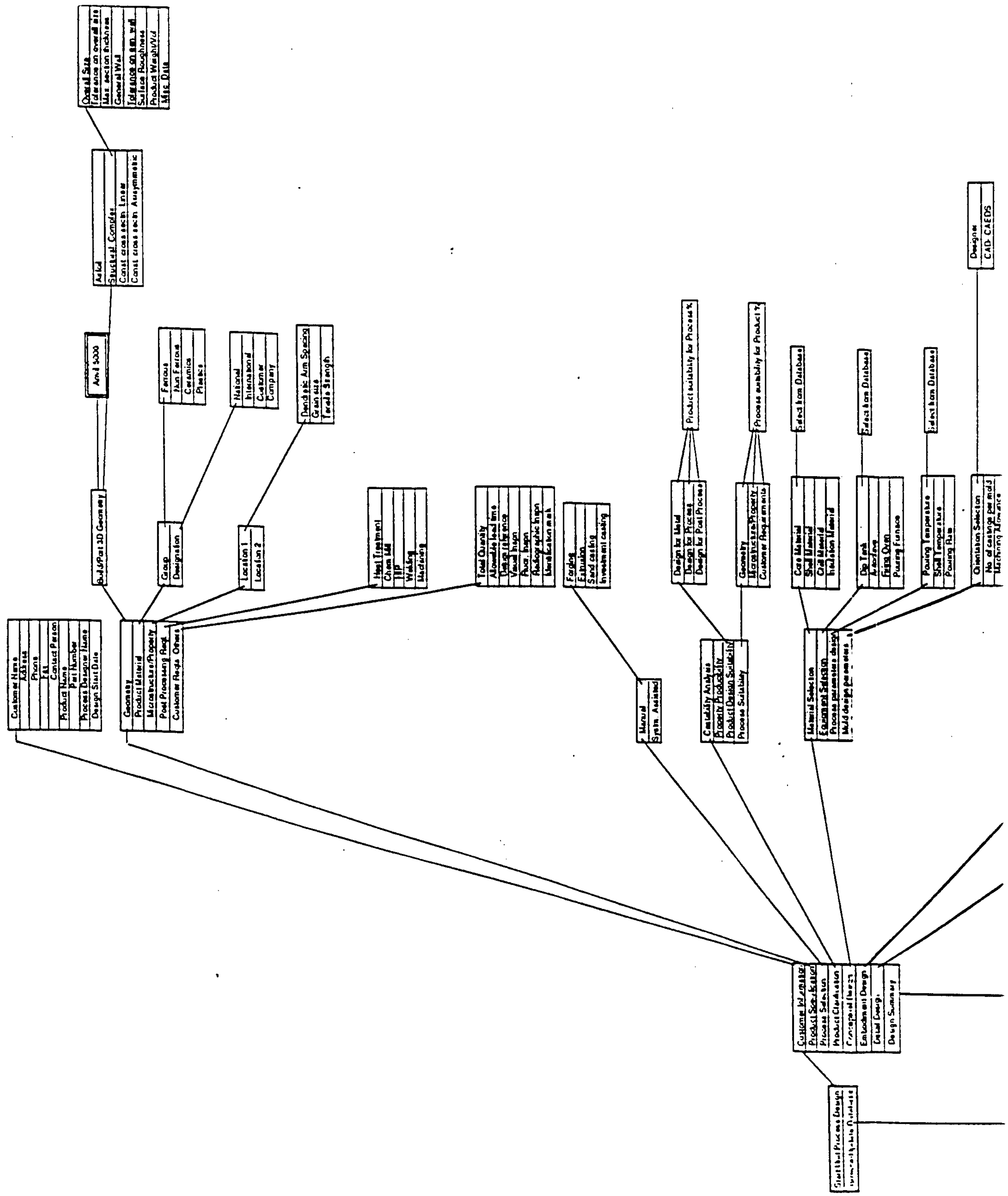
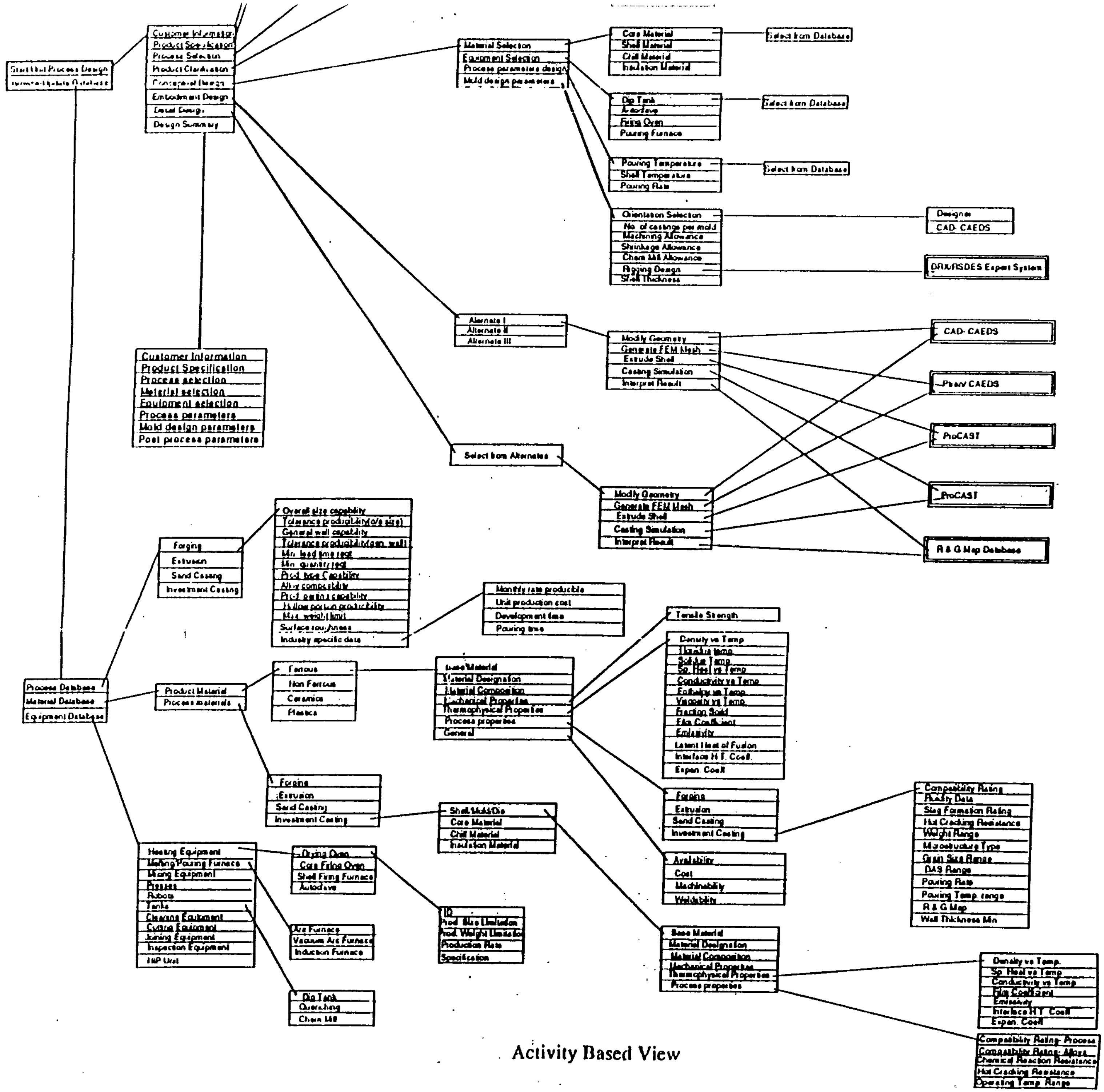


Figure 19. Global Design Methodology



Activity Based View

Planning is the third core design problem that can be facilitated by a shell's framework. Planning is difficult, because design tasks cannot be sequenced in detail. *It is possible to plan at a high level, but it is impossible to do details.* Planning requires status information about the design process. Knowledge integration shells can display a graphical picture of the workflow in progress by showing which activities have been accomplished and which ones are left to be done.

An advanced interface for doing simulation-based design with global and local design optimization capabilities would be some platforms with fully-independent software components, and it must allow for changing technologies. As design technologies change, it should be possible to exchange applications without redesigning the business process. *The ability to snap-out old applications and snap-on new ones should be provided.* An agent-based approach is feasible for SME's, because it requires only moderate coupling through communications and rules, and it reduces the cost of software development. An agent-based approach to design would decompose a large problem into smaller, autonomous problems that are amenable to optimization. The benefit of this approach is small problem solutions and small software components, which are easier to create, test and maintain. Small software components are also better suited for reuse.

Agents have many forms. An agent can be a computer, a human, an equipment agent, a material agent, a lubricant agent, etc. Agents can be enablers of agility, as they may represent a real world entity, simple sets of rules and be aware of such things as manufacturing conditions or design status. Agents can also be a cell or virtual enterprise. For example, agents can solicit work from customers, and, job agents can decompose the job into fractiles such as: *mill dies, stamp panel, and make door panel.* Applying agent-based design technology is viewed as a practical solution to the fundamental weaknesses of the design process. Set-based knowledge is used along with responsible agents. Design solutions can start with a solution, and, if it doesn't work, start over. Sets of possible solutions can range from a narrow set to broad-band sets. Both types of solutions are required by the DOD for affordable parts supply.

The numerical methods for modeling the forming of 3D material flow processes generally will be based on mathematical approximations that are appropriate for the geometrical complexity of the

problem at hand. Just as engineers today have to use a mix of software applications to solve different problems, a mix of numerical methods will be used in doing linked simulations of processes in the manufacturing chain. When the problem is classified as complex non symmetrical, the finite element will have to be used in place of simplified analytical solutions. Thus, a design system, which is based on the use of fully-independent applications, will allow an enterprise to mix and match the numerical methods to suit the nature of the design problem. Experience over the past decade indicates that designers prefer to use an application that can handle geometrical complexity and provide accurate solutions. Simplified models can be used during the conceptual stage of design, which is about 20 percent of the design process, to investigate design alternatives. However, more complex models that can treat complex geometries accurately must be used in the detail design stage, which is consistent with the fact that about 60 percent of the engineering resources are consumed in this stage of design.

To support this controversy, UES Software, Inc. has seen companies that started out using the finite difference numerical method that is simpler to use and set up than the finite element method employed by the ProCAST finite element application. Today, many of these companies are switching to the finite element method for several reasons: (1) Very accurate solutions can be obtained; (2) Complex geometries can be represented easily; (3) Neumann (flux) types boundary conditions can be treated easily when complex curved surfaces are involved; (4) Material flow analysis predictions are accurate when complex curved surfaces are encountered; (5) Mechanical and thermal contact between the workpiece and the die can be handled for general geometry; (6) Irregular meshes can be created to locally enhance the accuracy of the approximation and to treat different materials; (7) FEM is a general, flexible and robust numerical method; (8) FEM will always produce meaningful solutions, and it has been widely adopted in commercial applications for solving engineering problems; (9) Commercial tools are widely available for supporting the finite element method.

Finally, the FEM, when applied to metal forming, can simultaneously design the preform and die geometries when integrated into a Computer-aided Optimization (CAO) shell that automatically changes the design parameters to get an optimized solution for both the preform and the die. A

mix of FEM and other appropriate analysis tools can be used to optimize a sequence of processes and process parameters to satisfy the functional requirements of the part as specified by the product designer. It is important to note that lowest cost will not be achieved by process optimization alone. Lowest cost depends also on the efficiency of the total product realization process. Streamlining the acquisition process plays a crucial roll in producing affordable, high quality components and delivering them on an accelerated schedule. A total system approach must be taken.

The cost of high performance computing is dropping drastically, making design optimization a practical technique to use. The part supplier industries consist primarily of companies that employ less than 100 employees. This group of businesses prefers to use PC Workstations rather than UNIX Engineering Workstations. The Oak Ridge National Laboratory[3] will be testing an Intel desk-top Paragon Computer within the next two or three years that will be faster than the current models. The cost of high performance computing should be taken into account when decisions are made regarding the choice of numerical method.

[3] Dr. Thomas Zacharia, Oak Ridge National Laboratory (ORNL), Private Communications.

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